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Locating and Estimating Air Emissions from Sources of Polychlorinated Biphenyls (PCB)

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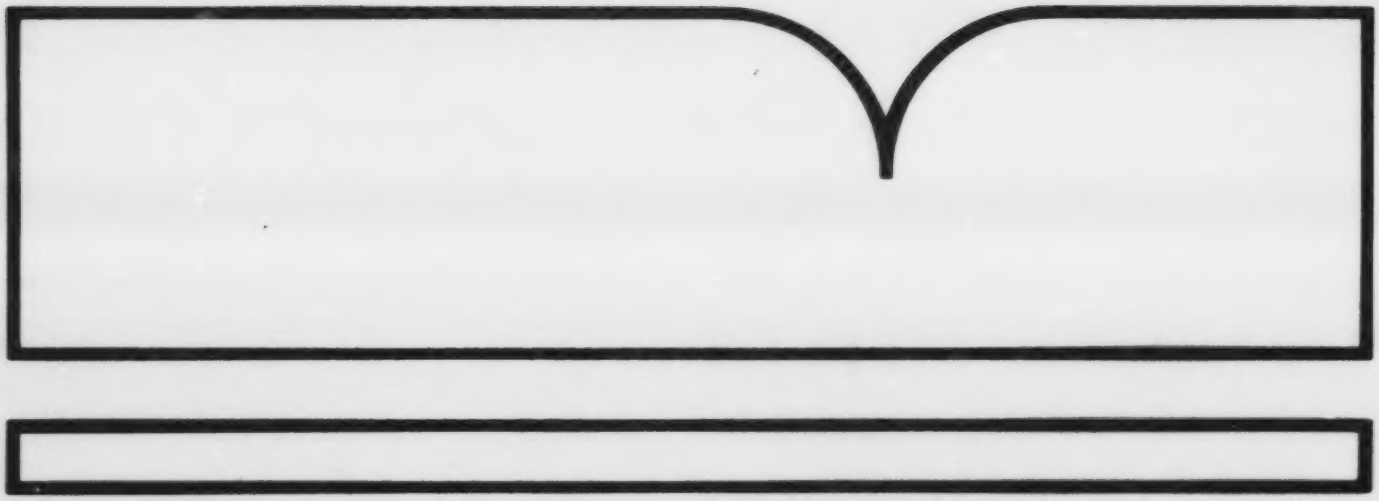
Research Triangle Park, NC

May 87



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Office of Air Quality
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May 1987

Air

EPA

Locating And Estimating Air Emissions From Sources Of Polychlorinated Biphenyls (PCB)

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16. ABSTRACT

To assist groups interested in inventorying air emissions of various potentially toxic substances, EPA is preparing a series of documents such as this to compile available information on sources and emissions of these substances. This document deals specifically with Polychlorinated Biphenyls. Its intended audience includes Federal, State and local air pollution personnel and others interested in locating potential emitters of Polychlorinated Biphenyls and in making gross estimates of air emissions therefrom.

This document presents information on 1) the types of sources that may emit Polychlorinated Biphenyls, 2) process variations and release points that may be expected within these sources, and 3) available emissions information indicating the potential for Polychlorinated Biphenyls release into the air from each operation.

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office Of Air And Radiation
Office Of Air Quality Planning And Standards
Research Triangle Park, North Carolina 27711

This report has been reviewed by the Office Of Air Quality Planning And Standards, U.S. Environmental Protection Agency, and has been approved for publication as received from the contractor. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, neither does mention of trade names or commercial products constitute endorsement or recommendation for use.

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SECTION 1
PURPOSE OF DOCUMENT

EPA, States and local air pollution control agencies are becoming increasingly aware of the presence of substances in the ambient air that may be toxic at certain concentrations. This awareness, in turn, has led to attempts to identify source/receptor relationships for these substances and to develop control programs to regulate emissions. Unfortunately, very little information is available on the ambient air concentrations of many of these substances or on the sources that may be discharging them to the atmosphere.

To assist groups interested in inventorying air emissions of various potentially toxic substances, EPA is preparing a series of documents such as this that compiles available information on sources and emissions of these substances. This document specifically deals with polychlorinated biphenyls (PCBs). Its intended audience includes Federal, State and local air pollution personnel and others who are interested in locating potential emitters of PCBs and making preliminary estimates of air emissions therefrom.

Because of the limited amounts of data available on PCB emissions, and since the configuration of many sources will not be the same as those described herein, this document is best used as a primer to inform air pollution personnel about 1) the types of sources that may emit PCBs, 2) source variations and release points that may be expected within these sources, and 3) available emissions information indicating the potential for PCBs to be released into the air from each source.

The reader is strongly cautioned that using the emissions information contained in this document will not yield an exact assessment of emissions from any particular source. Since insufficient data are available to develop statistical estimates of the accuracy of these emission factors, no estimate can be made of the error that would result when these factors are used to calculate emissions from any given source. It is possible, in some extreme cases, that orders-of-magnitude differences could result between actual and calculated emissions, depending on differences in source configurations,

control equipment and operating practices. Thus, in situations where an accurate assessment of PCB emissions is necessary, source-specific information should be obtained to confirm the existence of particular emitting operations, the types and effectiveness of control measures, and the impact of operating practices. A source test and/or material balance should be considered as the best means to determine air emissions directly from an operation.

This document presents information on rules governing the use and disposal of PCBs. The information contained herein represents the regulatory status of PCBs as of the compilation date of the document (February 1986). Because of the dynamics involved in regulating PCBs, rules are frequently revised. Therefore, the reader should consult references such as the Code of Federal Regulations to determine the current regulatory status.

SECTION 2

OVERVIEW OF DOCUMENT CONTENTS

As noted in Section 1, the purpose of this document is to assist Federal, State and local air pollution agencies and others who are interested in locating potential air emitters of polychlorinated biphenyls (PCBs) and making gross estimates of air emissions therefrom. Because of the limited background data available, the information summarized in this document does not and should not be assumed to represent the source configuration or emissions associated with any particular source.

This section provides an overview of the contents of this document. It briefly outlines the nature, extent and format of the material presented in the remaining sections of this report.

Section 3 of this document provides a brief summary of the physical and chemical characteristics of PCBs, their commonly occurring forms and an historical overview of their production and uses. With minor exceptions, PCBs are no longer produced in the United States (domestic production ceased in 1977) and have been used only in closed systems (e.g., transformers, capacitors) since 1971. A chemical use tree summarizes the quantities of PCBs consumed in various end use categories in the United States. This background section may be useful to someone who needs to develop a general perspective on the nature and uses of PCBs.

Section 4 of this document focuses on major industrial source categories that may discharge PCB air emissions. This section discusses disposal methods and sources of accidental releases of PCBs. For each major source category described in Section 4, available emissions information -- including emission factor estimates -- is presented that shows the potential for PCBs emissions.

The final section of this document summarizes available procedures for source sampling and analysis of PCBs. Details are not prescribed nor is any EPA endorsement given to any of these sampling and analytical procedures. At this time, EPA generally has not evaluated these methods. Consequently, this document merely provides an overview of applicable source sampling procedures, citing references for those interested in conducting source tests.

This document does not contain any discussion of health or other environmental effects of PCBs, nor does it include any discussion of ambient air levels or ambient air monitoring techniques.

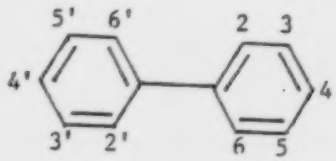
Comments on the contents or usefulness of this document are welcomed, as is any information on process descriptions, operating practices, control measures and emissions information that would enable EPA to improve its contents. All comments should be sent to:

Chief, Noncriteria Emissions Section (MD-14)
Air Management Technology Branch
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

SECTION 3
BACKGROUND

NATURE OF POLLUTANT

The term "polychlorinated biphenyls (PCBs)" refers to a class of organic chemicals produced by the chlorination of biphenyl. Ten classes of PCBs may be formed (these include monochlorobiphenyl, although it is not technically polychlorinated), depending on the specific number of chlorine substitutions on the biphenyl molecule. These compounds, in increasing order of chlorine substitution, are monochlorobiphenyl, dichlorobiphenyl, trichlorobiphenyl, and so on. Several isomers of each PCB molecule are possible (for a total of 209), but not all are likely to be formed during the manufacturing processes. The biphenyl structure with possible substitution sites is shown below:[1]



PCB molecules and their molecular weights are presented in Table 1. Table 2 presents properties of selected isomers.

In general, higher PCB chlorine content corresponds to greater resistance to chemical degradation. PCB isomers, which range from liquids to high melting crystalline solids, exhibit low solubility in water, low vapor pressure, low flammability, high heat capacity, moderate heat of vaporization, and low electrical conductivity. These properties, as well as favorable dielectric constants and suitable viscosity-temperature relationships, make them extremely advantageous for use as dielectric and heat transfer fluids.[6]

TABLE 1. COMPOSITION OF POLYCHLORINATED BIPHENYLS[2]

Compound	Empirical formula	Molecular weight[a]	Weight percent chlorine[a]	Number of isomers
Monochlorobiphenyl	$C_{12}H_9Cl$	188	18.6	3
Dichlorobiphenyl	$C_{12}H_8Cl_2$	222	31.5	12
Trichlorobiphenyl	$C_{12}H_7Cl_3$	256	41.0	24
Tetrachlorobiphenyl	$C_{12}H_6Cl_4$	290	48.3	42
Pentachlorobiphenyl	$C_{12}H_5Cl_5$	324	54.0	46
Hexachlorobiphenyl	$C_{12}H_4Cl_6$	358	58.7	42
Heptachlorobiphenyl	$C_{12}H_3Cl_7$	392	62.5	24
Octochlorobiphenyl	$C_{12}H_2Cl_8$	426	65.7	12
Nanochlorobiphenyl	$C_{12}HCl_9$	460	68.5	3
Decachlorobiphenyl	$C_{12}Cl_{10}$	494	79.9	1

[a]Based on Cl^{35}.

TABLE 2. MELTING POINTS AND SOLUBILITIES OF SOME PCB ISOMERS

Compound	CAS number[3]	Melting point[4] (°C)	Solubility in water[5] (mg/l)
Monochlorobiphenyls			
2-	2150-60-7	34	5.90
3-	--	--	3.50
4-	2051-62-9	77.7	1.19
Dichlorobiphenyls			
2,4-	--	--	1.40
2,2'-	13029-08-8	60.5	1.50
2,3'-	25569-80-6	--	--
2,4'-	34883-43-7	44.5-56	1.88
4,4'-	2050-68-2	149-150	0.08
Trichlorobiphenyls			
2,4,4'-	7012-37-5	57-58	0.085
2,2',3-	38444-78-9	28.1-28.8	--
2,2',5-	37680-65-2	43-44	--
2,4',5-	16606-02-3	67	--
2',3,4-	38444-86-9	65-66	0.078
Tetrachlorobiphenyls			
2,3,4,4'-	33025-41-1	142	--
2,2',3,3'-	--	--	0.034
2,2',3,5'-	41464-39-5	49-50	0.170
2,2',4,4'-	--	--	0.068
2,2',4,5'-	41464-40-8	66-68.5	--
2,2',5,5'-	35693-99-3	87-89	0.046
2,3',4,4'-	32598-10-0	127-127.5	0.058
2,3',4',5-	32598-11-1	104-105	0.041
3,3',4,4'-	32598-13-3	182-184	0.175
Pentachlorobiphenyls			
2,3,3',4,4'-	--	117-118.5	--
2,3,3',4',6-	38380-03-9	--	--
2,2',3,4,5'-	--	111.5-113	0.022
2,2',3,3',6-	52663-60-2	--	--
2,2',3,5',6-	38379-99-6	98.5-100	--
2,2',4,5,5'-	37680-73-2	76.5-77.5	0.031
2,2',4,4',5-	38380-01-7	--	--
2,2',3',4,5-	41464-51-1	81-82	--
2,3',4,4',5-	31508-00-6	112-113	--

(continued)

TABLE 2. (continued)

Compound	CAS number[3]	Melting point[4] (°C)	Solubility in water[5] (mg/l)
Hexachlorobiphenyls			
2,2',3,4,4',5-	35694-06-5	77-78	--
2,2',3,4,4',5'-	35065-28-2	114-114.5	--
2,2',3,3',4,6-	38380-05-1	--	--
2,2',3,3',6,6-	38411-22-2	--	--
2,2',4,4',5,5'-	35065-27-1	103-104	0.088
2,2',3',4,5,6'-	38380-04-0	--	--
Heptachlorobiphenyls			
2,2',3,4',5,5'-	35065-29-3	109-110	--
2,2',3,3'4,5,6'-	38441-25-5	130.5-130.7	--
2,2',3,3',4,4',5-	35065-30-6	134.5-135.5	--
Octochlorobiphenyl			
2,2',3,3',4,4',5,5'-	--	--	0.007
Decachlorobiphenyl	--	--	0.015

Individual PCB isomers have been prepared in the laboratory by various synthetic routes.[7] However, for commercial purposes, PCBs are used and sold as a mixture of isomers. Large-scale U.S. production of PCBs was stopped voluntarily in October 1977 because of the tendency of PCBs to accumulate and persist in the environment and because of their toxic effects.[7] The principal U.S. producer of PCBs was Monsanto Industrial Chemicals Company which made the products under the registered trademark of Aroclor. As presented in Table 3, several Aroclor products were marketed prior to 1977 with various compositions. After 1977, manufacture of PCBs in the U.S. was restricted to situations requiring special authorization or exemptions by EPA. Manufacture of PCBs currently consists of low level incidental generation associated with the production of other compounds and the manufacture of small quantities of pure PCBs for research and development.[82]

All Aroclor products are designated by a four digit number, usually beginning with the prefix 12 to represent the biphenyl starting material, and a second set of digits to represent the approximate chlorine percentage. For example, Aroclor 1242 is a chlorinated biphenyl containing approximately 42 percent chlorine. Aroclors beginning with the prefixes 25 and 44 are blends of PCBs and chlorinated terphenyls while the prefix 54 represents a chlorinated terphenyl mixture with no biphenyl. Aroclor 1016 contains 41 percent chlorine by weight but the penta-, hexa-, and heptachlorobiphenyl content has been significantly reduced.[8]

Commercial mixtures of PCBs have been produced by companies in countries other than the U.S. and have been sold under various tradenames with various systems for product identification. These companies' tradenames are discussed in the subsection titled "Overview of Production and Uses."

The commercial mixtures of PCBs have properties quite different from the individual isomers, particularly in crystallinity and liquid range. PCBs are generally chemically inert and react with other materials only under high temperatures or extreme conditions. They are insoluble in water, glycerol, and glycols but are soluble in most of the common organic solvents. PCBs are highly resistant to oxidation. They are permanently thermoplastic in the higher chlorination levels and are considered extremely useful in energy

TABLE 3. PERCENT COMPOSITION OF SELECTED AROCLORS[2]

Chlorobiphenyl	Aroclor Type					
	1221	1242	1248	1254	1260	1016
$C_{12}H_{10}$	11	<0.1		<0.1		<0.1
$C_{12}H_9Cl$	51	1		<0.1		1
$C_{12}H_8Cl_2$	32	16	2	0.5		20
$C_{12}H_7Cl_3$	4	49	18	1		57
$C_{12}H_6Cl_4$	2	25	40	21		21
$C_{12}H_5Cl_5$	0.5	8	36	48	12	1
$C_{12}H_4Cl_6$		1	4	23	38	<0.1
$C_{12}H_3Cl_7$		<0.1		6	41	
$C_{12}H_2Cl_3$					8	
$C_{12}HCl_9$					1	
$C_{12}Cl_{10}$						

transfer applications. However, under elevated temperatures, the chlorine can react with metal to cause corrosion.[7] Chemical and physical properties of selected Aroclors are presented in Tables 4 and 5.

PCBs are not reactive chemically under normal environmental conditions. However, their use in quenching of heated metals, as heat-transfer media, and in transformer oil, may lead to the formation of degradation products such as dibenzofurans, polychloroquaterphenyls, polychloroquaterphenyl ethers, polychloroterphenyls, and oxygen-containing polymerics.[10]

Photodegradation of PCBs produces a variety of products via such pathways as chlorine replacement by hydrogen or hydroxyl groups, rearrangement, or condensation. Replacement of chlorine by hydroxyl groups at the ortho positions allows oxygen to bind in a similar position on the other ring, resulting in the formation of chlorodibenzofurans. Both heat and light can accelerate this process. However, while some experiments have indicated chlorodibenzofurans as a product of the process, other tests have resulted in no chlorodibenzofurans being detected. Because of the mixed results, no assessment of the accumulation of chlorodibenzofurans due to photodegradation of PCBs can be made.[10]

Biodegradation of PCBs has been reported to depend on the degree of chlorination. Although lower chlorinated biphenyls are readily transformed by bacteria, biodegradation of the pentachlorophenyls may be extremely slow, and that of hexa- and higher chlorinated biphenyls is practically negligible.[11]

PCBs are remarkable among organic industrial chemicals for their low solubility in water, their high octanol/water partition coefficients, accumulation coefficients, and their resistance to in-vivo degradation. As a result, they exhibit extraordinarily high values for bioaccumulation in animal tissues, especially in fish and other aquatic organisms. Bioaccumulation in fish may take place either through ingestion of contaminated food organisms or by direct absorption through the skin.[12]

OVERVIEW OF PRODUCTION AND USES

PCBs were first formulated in 1881 and were manufactured on a commercial scale in the United States as early as 1929.[13] Monsanto was the principal manufacturer in the United States until 1977 when they voluntarily ended

TABLE 4. CHEMICAL AND PHYSICAL PROPERTIES OF AROCLORS 1016 THROUGH 1260 [8,9]

Aroclor	1016	1221	1232	1242	1248	1254	1260
CAS registry no.	12674-11-2	11104-28-2	11141-16-5	53469-21-9	12672-29-6	11097-69-1	11096-82-5
Appearance	Clear, mobile oil	Clear, mobile oil	Clear, mobile oil	Clear, mobile oil	Clear, mobile oil	Light-yellow viscous liquid	Light-yellow soft, sticky resin
Weight % chlorine	41	20.5-21.5	31.4-32.5	42	48	54	60
Approx. mol. wt.	257.5	188.64	223.1	257.5	291.9	326.5	360.7
Stability	inert	inert	inert	inert	inert	inert	inert
Color, maximum	40 APHA	100 APHA	100 APHA	100 APHA	100 APHA	100 APHA	150 APHA
Acidity, mg KOH/g	NA	0.014	0.014	0.015	0.010	0.010	0.014
Moisture, ppm	NA	NA	NA	50	50	50	50
Ave. coefficient of expansion, cc/cc/°C	NA	0.00071 (15°-40°C)	0.00073 (25°-100°C)	0.00068 (25°-65°C)	0.00070 (25°-65°C)	0.00066 (25°-65°C)	0.00067 (20°-100°C)
Specific gravity	1.362-1.372 (25°/15.5°C)	1.182-1.192 (25°/15.5°C)	1.270-1.280 (25°/15.5°C)	1.381-1.392 (25°/15.5°C)	1.405-1.415 (65°/15.5°C)	1.495-1.505 (65°/15.5°C)	1.555-1.566 (90°/15.5°C)
Density, lb/gal, 25°C	11.40	9.85	10.55	11.50	12.04	12.82	13.50
Solubility in H_2O, mg/l @ 25°C	0.016	0.8-5.8	0.062	0.016	0.016-0.04	0.01-0.012	0.00095
Boiling point, °C							
Range @ 3 mm Hg.	155-195	109	NA	155-195	165-210	180-220	195-245
Average @ 760 mm Hg.	329	267	317	329	355	374	402.5
Vapor pressure, mm Hg							
@ 25°C	0.00057	NA	NA	0.00057	0.00018	0.000032	0.000013
@ 37.8°C	0.0020	NA	0.005	0.0020	0.00072	0.00015	0.000044

(continued)

TABLE 4. (continued)

Aroclor	1016	1221	1232	1242	1248	1254	1260
Antoine constants							
A	8.06573	7.86894	NA	8.06573	7.49507	7.34306	10.0201
B	2910.95	2426.18	NA	2910.95	2587.53	2501.24	5172.89
C	232.41	219.16	NA	232.41	205.4	186.35	322.04
w/temp.range, °C	25-330	89-270	NA	25-330	25-360	25-380	25-405
Specific heat, cal/gm-°C							
@ 10°C	NA	NA	NA	0.272	0.257	0.239	NA
@ 25°C	NA	NA	NA	0.293	0.277	0.261	0.228
@ 38°C	NA	NA	NA	0.282	0.265	0.245	NA
Heat vaporization @NBP, cal/gram	61	62.6	NA	61	54	50	48
Ideal gas heat capacity, cal/gmole-K @ 25°C	51.22**	42.89*	47.08*	51.22*	55.41*	59.55*	63.71*
Enthalpy of formation, Kcal/gmole @ 25°C	20.72**	35.92*	28.32*	20.72*	13.12*	5.52*	NA
Entropy, Gibbs/gmole @ 25°C	120.09**	105.35*	112.72*	120.09*	127.46*	134.83*	142.20*
Heat of combustion, Kcal/gmole @ 25°C	-1351.62**	-1424.62*	-1388.12*	-1351.62*	-1315.12*	-1278.62*	-1242.12*
Critical pressure, atm.	26.**	30.*	NA	26.*	NA	NA	NA
Critical temp., K	859.2**	778.5*	NA	859.2*	NA	NA	NA
Critical compressibility, dimensionless	0.24**	0.25*	NA	0.24*	NA	NA	NA

(continued)

TABLE 4. (continued)

Aroclor	1016	1221	1232	1242	1248	1254	1260
Distillation range, °C, corrected (ASTM D-20, modified)	323-356	275-320	290-325	325-366	340-375	365-390	385-420
Evaporation loss, % 100°C, 6 hr	NA	1.0-1.5	1.0-1.5	0-0.4	0-0.3	0-0.2	0-0.1
(ASTM D-6, mod.) 163°C, 5 hr	NA	NA	NA	3.0-3.6	3.0-4.0	1.1-1.3	0.5-0.8
Flash point, °C	170	141-150	152-154	176-180	193-196	NTBP	NTBP
(Cleveland Open °F Cup)	NA	286-302	305-310	348-356	379-384	NTBP	NTBP
Fire point, °C	NTBP	176	238	NTBP	NTBP	NTBP	NTBP
(Cleveland Open °F Cup)	NTBP	349	460	NTBP	NTBP	NTBP	NTBP
Pour point, °C	NA	1(crystals)	-35.5	-19	-7	10	31
(ASTM E-97) °F	NA	34(crystals)	-32	2	19.4	50	88
Refractive index, n D-20 20°C	1.622-1.624 (@ 25°C)	1.617-1.618	1.620-1.622	1.627-1.629	1.630-1.631	1.629-1.641	1.647-1.649
Viscosity, seconds Saybolt Universal (ASTM D-83)							
100°F (37.8°C)	71-81	38-41	44-51	82-92	185-240	1800-2500	-
130°F (54.4°C)	-	35-37	39-41	49-56	73-80	260-340	3200-4500
210°F (98.9°C)	-	30-31	31-32	34-35	36-37	44-48	72-78

NA = Not available.
NTBP = None to boiling point.
* = Estimated.
** = Estimated based on Aroclor 1242 properties.

TABLE 5. CHEMICAL AND PHYSICAL PROPERTIES OF AROCLORS 1262 THROUGH 5460 [8]

Aroclor	1262	1268	1270	2565	4465	5442	5460
CAS registry no.	37324-23-5	11100-14-4			12642-23-8	12642-23-8	11126-42-4
Appearance	Light-yellow sticky viscous resin	White to off-white powder	White crystalline powder	Black, opaque brittle resin	Clear, light-yellow resin	Clear, yellow sticky resin	Clear, yellow-to-amber, brittle resin or flakes
Color, maximum	150 APHA	1.5 NPA	NA	NA	2 NPA	2 NPA	2 NPA
Weight % chlorine	61.5-62.5	68	71	65	65	42	58.5-60.6
Acidity, mg KOH/g	0.014	0.05	NA	1.4	0.05	0.05	0.05
Ave. coefficient of expansion, cc/cc/°C	0.00064 (25°-65°C)	0.00067 (20°-100°C)	NA NA	0.00066 (25°-65°C)	0.00061 (25°-65°C)	0.00123 (25°-99°C)	0.00179 (25°-124°C)
Specific gravity	1.572-1.583 (90°/15.5°C)	1.804-1.811 (25°/25°C)	1.944-1.960 (25°/25°C)	1.734 (25°/25°C)	1.670 (25°/25°C)	1.470 (25°/25°C)	1.670 (25°/25°C)
Density, lb/gal, 25°C	13.72	15.09	16.30	14.44	13.91	12.24	13.91
Distillation range; °C, corrected (ASTM D-20, modified)	390-425	435-450	450-460	NA	230-320 (4 mm Hg)	215-300 (4 mm Hg)	280-335 (5 mm Hg)
Evaporation loss, % 100°C, 6 hr	0-0.1	0-0.06	NA	NA	0-0.02	0.01	NA
(ASTM D-6 mod.) 163°C, 5hr	0.5-0.6	0.1-0.2	NA	0.2-0.3	0.2-0.3	0.2	0.03
Flash point, °C (Cleveland Open °F Cup)	NTBP NTBP	NTBP NTBP	NTBP NTBP	NA NA	NTBP NTBP	247 477	NTBP NTBP
Fire point, °C (Cleveland Open °F Cup)	NTBP NTBP	NTBP NTBP	NTBP NTBP	NA NA	NTBP NTBP	>350 >662	NTBP NTBP

TABLE 5. (continued)

Aroclor	1262	1268	1270	2565	4465	5442	5460
Pour point, °C (ASTM E-97) °F	38-38 99 115	NA NA	NA NA	NA NA	NA NA	46 115	NA NA
Softening point, °C (ASTM E-97) °F	NA NA	150-170 302-338	249-300 NA	66-72 149-162	60-66 140-151	46-52 115-126	98-105 208-222
Refractive index, n D-20 20 °C	1.6501-1.6517	NA	NA	NA	1.664-1.667	NA	1.660-1.665
Viscosity, seconds Saybolt Universal (ASTM D-83)							
100°F (37.8°C)	600-850	NA	NA	NA	NA	NA	NA
130°F (54.4°C)	(160°F; 71°C)	NA	NA	NA	90-150	NA	NA
210°F (98.9°C)	86-100	NA	NA	NA	(265°F; 130°C)	300-400	NA

NA = Not available.
NTBP = None to boiling point.

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production because of widespread environmental concerns about PCBs. Monsanto marketed PCBs under the tradenames "Askarel" and "Aroclor."[8,13] Dielectric fluids containing PCBs have been marketed by several companies under a variety of tradenames which are listed in Table 6.

Before 1977, PCBs were produced by the chlorination of biphenyl with anhydrous chlorine, using iron filings or ferric chloride as catalysts. The crude product was purified to remove traces of hydrogen chloride and catalyst.[8] Commercially produced PCBs contained no major components other than chlorobiphenyls. Small amounts of chlorodibenzofurans have been detected in PCB mixtures, possibly as a result of aqueous alkaline washing and steam distillation in the production process. PCB mixtures were sold in two grades: a purified grade and a darker, less pure, technical grade.[15]

Uses of PCBs are presented in Figure 1. Prior to 1957, virtually all PCBs were used in the manufacture of electrical transformers and capacitors. As discussed earlier, PCBs exhibit low flammability, high heat capacity, and low electrical conductivity and are virtually free of fire and explosion hazards. Consequently, PCBs can be used where failures of oil insulated transformers would present a potential danger to life and property. PCBs were therefore used wherever fire protection was particularly important -- for about 5 percent of all transformers.[17]

The PCB containing fluids used in transformers are called "askarels."[18] These fluids typically contain from 60 to 70 percent PCBs by weight, and from 30 to 40 percent chlorobenzene.[19] The amount of askarel contained in a transformer varies with transformer size. The literature reports that the quantity ranges from 150 to 1,890 liters (40 to 500 gal) which weighs 235 to 2,932 kg (516 to 6,450 lb).[20]

PCBs have been used in electrical capacitors for many of the same reasons. They are needed for safety, reliability and long life and to achieve sizes compatible with equipment and installation requirements. PCBs were used principally in high voltage power capacitors for power factor correction in the distribution of electric power; in low voltage power capacitors installed in industrial plants (typically in large motors); in ballast capacitors to improve the efficiency of lighting systems; and in small industrial capacitors

TABLE 6. COMMON TRADE NAMES FOR PCB DIELECTRIC FLUIDS[13,14]

Askarel	Inerteen
Aroclor	Kennechlor
Aroclor B	MCS 1489
Asbestol	Nepolin
Chlorextol	No-Famol
Chlorinol	Phenoclor
Chlorphen	Pydraul
Chlophen	Pyralene
Diachlor	Pyranol
Diacolor	Pyroclor
DK	Saf-T-Kuhl
Dykanol	Santotherm
EEC-18	Solvol
Elemex	Therminol
Eucarel	
Fenclor	
Hyvol	

			USE		PERCENT	
			CATEGORY	PRODUCT	UNTIL 1971	AFTER 1971
Biphenyl ($C_{12}H_{10}$) + Chlorine (Cl_2)	---------->	Polychlorinated Biphenyl ($C_{12}H_{10-n}Cl_n$)	Closed Electrical Systems	Transformers, Capacitors, Other (Minor) Electrical Insulating/Cooling Applications	61%	100%
			Nominally Closed Systems	Hydraulic Fluids, Heat Transfer Fluids, Lubricants	13%	0%
			Open-End Applications	Plasticizers, Surface Coatings, Ink and Dye Carriers, Adhesives Pesticide Extenders, Carbonless Copy Paper, Dyes	26%	0%
					100%	100%

Figure 1. Chemical use trees for PCBs. 16

for power factor improvement in such equipment as air conditioning units, pumps, fans, etc.[21] The large high voltage capacitors typically weigh 54 kg (120 lb) of which 11 kg (25 lb) are PCBs, while the small ballast capacitors weigh 1.6 kg (3.5 lb) of which 0.05 kg (0.1 lb) are PCBs.[22]

Transformers and capacitors continued to be the main products using PCBs after 1957, however, additional industrial applications began to absorb a share of PCB production at this time. The relative product use of PCBs for industrial application between 1957 and 1971, when Monsanto restricted sales to closed systems (capacitor and transformer applications), is shown in Figure 2. Additional PCB applications included uses in hydraulic fluids and lubricants, plasticizers, heat transfer fluids, investment castings, and in miscellaneous industrial applications. These applications are considered either "nominally closed" or "open systems" due to the ease with which the PCBs may enter the atmosphere during use (when compared to transformer/capacitor use). The grade of Aroclor used in each of the aforementioned applications is shown in Table 7. PCBs were employed in industrial hydraulic and lubricant applications because they exhibited good heat and fire resistance and they were relatively inexpensive additives that depressed fluid pour points. These qualities are essential when hydraulic fluids are used in or near a hot operating environment. For example, hydraulic dye casting machinery and aircraft engines are two applications where moderately high operating temperatures combined with a high probability for accidents often lead to hydraulic system leaks and the possibility of fire. PCBs were used as lubricants due to the previously mentioned qualities, and also because of their oxidation and foam resistance characteristics and their low vapor pressure.[25]

PCBs gained widespread use in plasticizers because PCBs are permanently thermoplastic, chemically stable, non-oxidizing, non-corrosive, fire resistant, and are excellent solvents. In addition, they are not normally attacked by acids, alkalines or water and are insoluble in water, glycerol and glycols. These compatibility properties are especially useful in plasticizers. A plasticizer is a material incorporated in a plastic to increase its workability and flexibility. A plasticizer typically is added to

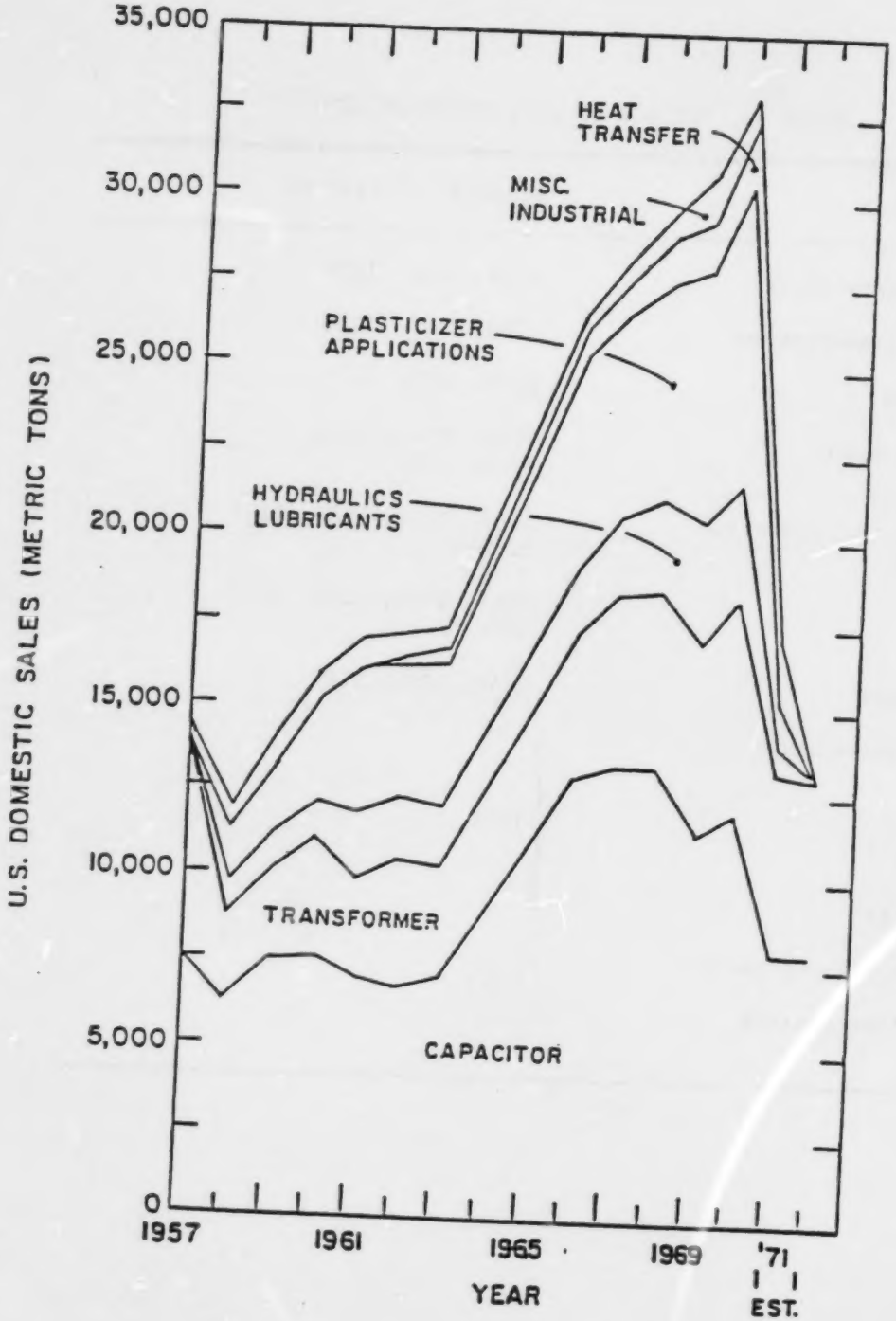

Figure 2. Domestic sales of Monsanto's Polychlorinated Biphenyls in the U.S. (by use).[23]

TABLE 7. THE USE OF PCBs PRIOR TO 1970[24]

Use	Grade(s) of Aroclor
Electrical capacitors	1221, 1242, 1254
Electrical transformers	1242, 1254, 1260
Vacuum pumps	1248, 1254
Hydraulic fluids	1232, 1242, 1248, 1254, 1260
Plasticizer in synthetic resins	1248, 1254, 1260, 1262 1268
Adhesives	1221, 1232, 1242, 1248, 1254
Wax extenders	1242, 1254, 1268
Pesticide extenders	1254
Inks	1254
Lubricants	1254
Cutting oils	1254
Carbonless copying paper	1242
Heat transfer systems	1242

change the viscosity, make the plastic softer (lower its elastic modulus) or impact some other specific property. PCBs added several of these properties at a relatively low cost.[26]

Heat transfer fluids are used to absorb thermal energy from a source and, by cooling or phase change, deliver heat to a place of utilization. PCBs have been used for these fluids due to their fire resistance, their low power and viscosities, their good thermal stability and their high heat capacity.[27] In addition, they are inert and are relatively inexpensive. However, the principle reason for use of PCBs as heat transfer fluids is their fire-resistance. This is a critical factor in cases where the possibility exists that fire from high temperature leaks could endanger life and property.

PCBs were also used by the investment casting industry in the production and subsequent use of PCB-filled pattern waxes. The investment casting process is a lost wax casting process. A pattern is molded by the injection of the molten casting wax into a metallic die where the wax cools and solidifies to form the desired shape. The wax pattern is then surrounded by a slurry containing a refractory ceramic (known as the investment) to form the final mold. After the model dries to an appropriate strength, the wax pattern is smelted in an autoclave and the wax is recovered for possible future use or disposal. Residues of wax remaining in the pores of the ceramics mold are burned out in a furnace at 1000°C to 1100°C. Molten metal may then be poured into the cavity of the ceramic mold to form a casting. Addition of fillers such as PCBs or polychlorinated triphenyls (PCTs) to investment casting waxes was a development of the 1960's. By reducing the wax content through addition of low shrinkage fillers, volumetric shrinkage of the ceramic mold may be controlled. Between 300,000 and 500,000 kg of PCBs were imported from Italy for this application in 1972.[28]

PCBs are also found used in a host of minor industrial uses. They were used in laminating adhesive formulations involving polyurethanes and polycarbonates to prepare safety and acoustical glasses. The laminates improved strength and resistance to delamination over a broad temperature range, and improved sound absorption and energy dissipation properties. PCBs were also used in adhesive formulas to improve toughness and resistance to oxidative and thermal degradation when laminating ceramics and metals.[29]

PCBs were employed with textile coating mixtures for ironing board covers, as coatings for polypropylene films and yarns and in sealing formulations to waterproof canvas. These applications took advantage of PCBs' ability to resist photochemical degradation, oxidation and fire.[30]

PCBs were used in paints and varnishes to impart weatherability, luster and adhesion. In combination with other plasticizers, they were employed to prepare film casting solutions for electrical coatings, insulating tapes and protective lacquer. PCBs are compatible with epoxy resins and give good final hardness and impact resistance to resin. These PCB resins were then used as protective coatings for metals. In addition, PCBs were used in sealing and caulking compositions to seal joints against water, dust, gas, heat and certain chemicals. Here, again, the good chemical and physical resistance properties of PCBs, their elasticity, weatherability and relative low cost made PCBs a valuable additive.[31]

Chlorinated biphenyls were employed as part of the formulations used to prepare pressure sensitive record and colored copying papers, including graphic duplicating processes, xerographic transfer processes and solvent free printing. PCBs used in this application later found their way into many paper products, when the carbonless copy paper was recycled into a host of other paper goods, including food packaging.[32]

Finally, PCBs were employed for an assortment of miscellaneous uses such as a soil erosion retardant, in combined insecticide and bactericide formulations, in plastic decorative articles, as a metal quencher and as an aid in fusion cutting of stacked metal plates.[33]

By 1970, 60 percent of PCBs sales were for closed system electrical and heat transfer uses, 25 percent for plasticizer applications, 10 percent for hydraulic fluids and lubricants, and less than 5 percent for miscellaneous applications such as surface coatings, adhesives, printing inks, and pesticide extenders. In late 1970 Monsanto confined PCB sales to closed systems. By 1971, 90 percent of all PCBs were used in this manner, and by 1972, 100 percent.[24] Monsanto ceased manufacture of PCBs completely in 1977 due to increased environmental concerns and the availability of replacement products to the electrical industry.[7]

On February 17, 1978, EPA issued a rule governing the marking and disposal of PCBs.[15] The rule applied to any substance, mixture, or item with 500 ppm or greater PCB concentrations. In 1979, EPA issued the PCB Ban Rule which superceded the previcus labeling and disposal regulation and lowered the cut-off point from 500 ppm to 50 ppm. The final rule was published in the Federal Register on May 31, 1979, and specifically does the follcwirg:

(1) classifies the use of PCBs in transformers, capacitors, and electromagnets as "totally enclosed;"

(2) prohibits, unless authorized or exempted by EPA, the manufacturing, processing, distribution in commerce, and the use of PCBs except in a totally enclosed manner;

(3) provides authorizations for certain processing, distribution in commerce, and use of PCBs in a non-totally enclosed manner.

(4) prohibits waste oil containing any detectable concentrations of PCBs from being used as a sealant, coating, or dust control agent.

Also, the February 17, 1978 PCB Disposal and Marking Rule requirements were integrated into the PCB Ban Rule.[15]

Because the Toxic Substances Control Act (TSCA) considers the term "import" to be synonomous with "manufacture", no PCBs (except waste) could be imported or exported after July 2, 1979 under the Ban Rule unless an exemption was obtained. Anyone wanting an exemption from the PCB manufacturing/importation ban or the PCB processing/distribution ban must petition EPA for it. In some instances, individuals may not have to seek separate exemptions when the Agency grants "class" exemptions from certain processing and commercial distribution bans. EPA also could grant exceptions, known as authorizations, without a specific request from those who would benefit from the authorization to enable the continued processing, distribution, or use of PCBs in a non-totally enclosed manner after July 2, 1979. Exemptions are only valid for a maximum of one year, while authorizations may be granted for longer periods of time. Examples of non-totally enclosed PCB activities and uses which have been authorized by EPA are as follows:[14]

- Servicing PCB Transformers and PCB-Contaminated Transformers;
- Use in and Servicing of Railroad Transformers;
- Use in and Servicing of Mining Equipment;
- Use in Heat Transfer Systems;
- Use in Hydraulic Systems;
- Use in Carbonless Copy Paper;
- Pigments;
- Servicing Electromagnets;
- Use in Natural Gas Pipeline Compressors;
- Small Quantities for Research & Development;
- Miscroscopy Mounting Medium.

On October 30, 1980, in response to a petition from the Environmental Defense Fund, the U.S. Court of Appeals for the District of Columbia Circuit set aside portions of the May 31, 1979 Ban Rule. The court remanded the set aside portions to EPA for further action. Responding to the court order, EPA, on August 25, 1982, amended the May 31, 1979 rule by authorizing the totally enclosed use of PCBs in certain electrical equipment.[33] Among other things, this amendment authorizes the continued use of PCB small capacitors, the use of PCB large capacitors until 1988 or longer if certain conditions are met, and the use of PCB transformers and PCB-contaminated transformers, if certain conditions are met. The 1979 rule was further amended on October 21, 1982 when EPA issued a rule excluding from regulation the manufacture, processing, distribution in commerce, and use of PCBs created in closed manufacturing processes and controlled waste manufacturing processes.[33] EPA considers these PCBs to present very low risks. This rule permits the manufacture, processing, and distribution in commerce of PCBs without an exemption, provided that (1) the PCBs are released only in concentrations below the practical limits of quantitation for PCBs in air emission, water effluents,

products, and process wastes and (2) the wastes from these manufacturing processes are controlled and disposed of in accordance with the methods for disposal specified in the rule.[33]

On July 10, 1984, a third amendment to the 1979 rule was issued by EPA that excludes from the TSCA ban on PCBs certain processes that inadvertently generate PCBs in low level concentrations. Other rules were issued by EPA on the same date which dealt with over 100 pending exemption petitions to manufacture, process and distribute PCBs in commerce and which authorized the use of PCBs in certain kinds of microscopy, and research and development situations. EPA believes that the PCBs permitted by these activities would not present an unreasonable risk to human health or the environment.[33]

Results from a study of the current distribution of PCBs in the United States are as follows:

Category	Amount	Percent
Presently in use	3.40×10^8 kg	60%
In landfills and dumps	1.32×10^8 kg	23%
Released to environment	0.68×10^8 kg	12%
Destroyed	0.25×10^8 Kg	5%
TOTAL	5.65×10^8 Mg	100%

The results indicate that of the 5.65×10^8 kilograms (1.25×10^9 lbs) sold between 1930 and 1977, 95 percent remains in service, in landfills, or at large in the environment.[13]

SECTION 4
PCB EMISSION SOURCES

The development of emission factors for PCBs presents unique problems not encountered with standard emission factor development. These problems can be summarized as follows:

- PCBs have not been produced (except for limited cases) in the U.S. since 1977;
- PCBs have not been used in "open systems" (those with maximum atmospheric release potential) since 1971;
- Atmospheric evaporation, transformation and degradation of PCBs are complex phenomena dependent upon many variables; and
- Little research has been conducted to quantify PCB emission rates from product use and/or disposal.

Due to the ban on PCB production and open system use, PCB emissions from these sources have effectively been halted. Release to the environment as a consequence of all PCB use occurred prior to 1970 and was, for the most part, unintentional. The major mechanisms by which PCBs are lost to the environment include aerosolization (during leaks and spills), adsorption onto particulates (during combustion), and volatilization. Prior to 1970, the major pathways by which PCBs were released during use included spillage and vaporization of PCB containing paints, coatings and plastics; migration and leaching from surface coatings and packaging; leakage from faulty heat exchange systems and partially sealed hydraulic systems; and burnout of PCB containing ballasts in fluorescent light fixtures.[34] As the PCB-containing products have been discarded, the major source of PCB emissions into the environment has shifted to disposal/destruction methods (e.g., incineration, landfilling). Incomplete combustion in an incinerator or boiler may result in the release of PCBs or PCB byproducts. Another source of PCB emissions is accidental release due to failure of an existing piece of PCB equipment (resulting in spills or leaks)

or an accident (e.g., fire) to a piece of PCB equipment in service. This section discusses these activities and presents information on the potential for PCB releases from each.

DISPOSAL/DESTRUCTION METHODS

EPA's PCB regulations (40 CFR 761) set specific disposal requirements for PCBs and PCB items currently in service.[35] The requirements are summarized in Figure 3. The regulations make distinctions between PCBs, PCB articles (items that contain PCBs and whose surface(s) have been in direct contact with PCBs), and PCB containers (barrels, drums, containers, etc. that contain PCBs and whose surface(s) have been in direct contact with PCBs). Within these categories, the regulations make a further distinction based on the PCB concentration of the waste. Acceptable PCB disposal technologies are then based on this PCB concentration. There are a limited number of disposal options, summarized as follows:

- "Annex I" Incinerators;
- High Efficiency Boilers;
- "Annex II" Chemical Waste Landfills; and
- Other Approved Disposal Methods.

A brief review of these disposal techniques will serve to highlight the principal characteristics of each.

Annex I Incinerators

Technology Descriptions--

These incinerators take their designation from the technical standards and other criteria that they are required to meet when destroying liquid PCB wastes. These standards and criteria are found in Annex I of EPA's PCB

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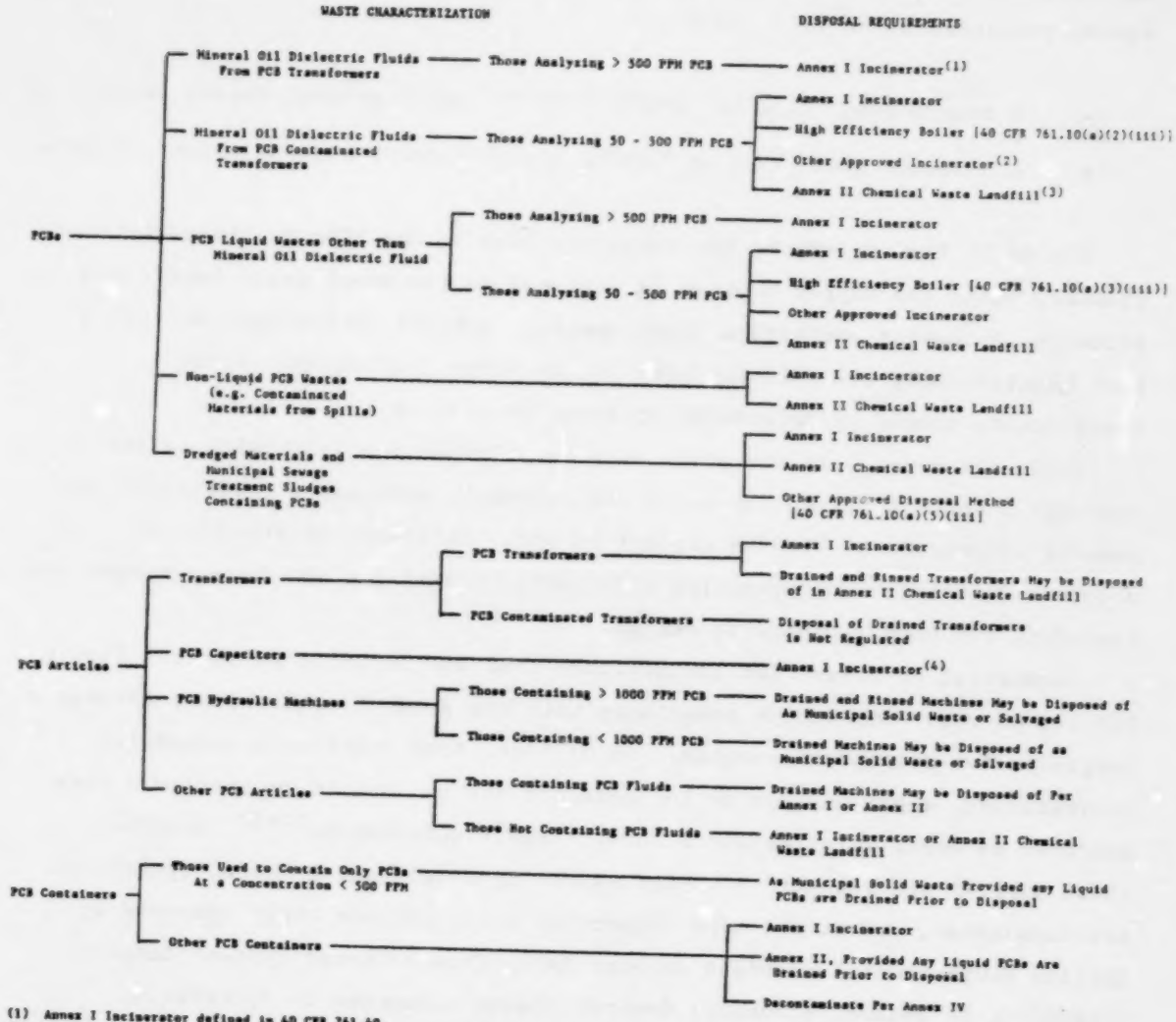
WASTE CHARACTERIZATION
DISPOSAL REQUIREMENTS
PCBs
Mineral Oil Dielectric Fluids From PCB Transformers
Those Analyzing > 500 PPM PCB
Annex I Incinerator(1)
Mineral Oil Dielectric Fluids From PCB Contaminated Transformers
Those Analyzing 50 - 500 PPM PCB
Annex I Incinerator
High Efficiency Boiler [40 CFR 761.10(a)(2)(iii)]
Other Approved Incinerator(2)
Annex II Chemical Waste Landfill(3)
PCB Liquid Wastes Other Than Mineral Oil Dielectric Fluid
Those Analyzing > 500 PPM PCB
Annex I Incinerator
Those Analyzing 50 - 500 PPM PCB
Annex I Incinerator
High Efficiency Boiler [40 CFR 761.10(a)(3)(iii)]
Other Approved Incinerator
Annex II Chemical Waste Landfill
Non-Liquid PCB Wastes (e.g. Contaminated Materials from Spills)
Annex I Incinerator
Annex II Chemical Waste Landfill
Dredged Materials and Municipal Sewage Treatment Sludges Containing PCBs
Annex I Incinerator
Annex II Chemical Waste Landfill
Other Approved Disposal Method [40 CFR 761.10(a)(5)(iii)]
PCB Articles
Transformers
PCB Transformers
Annex I Incinerator
Drained and Rinsed Transformers May be Disposed of in Annex II Chemical Waste Landfill
PCB Contaminated Transformers
Disposal of Drained Transformers is Not Regulated
PCB Capacitors
Annex I Incinerator(4)
PCB Hydraulic Machines
Those Containing > 1000 PPM PCB
Drained and Rinsed Machines May be Disposed of As Municipal Solid Waste or Salvaged
Those Containing < 1000 PPM PCB
Drained Machines May be Disposed of as Municipal Solid Waste or Salvaged
Other PCB Articles
Those Containing PCB Fluids
Drained Machines May be Disposed of Per Annex I or Annex II
Those Not Containing PCB Fluids
Annex I Incinerator or Annex II Chemical Waste Landfill
PCB Containers
Those Used to Contain Only PCBs At a Concentration < 500 PPM
As Municipal Solid Waste Provided any Liquid PCBs are Drained Prior to Disposal
Other PCB Containers
Annex I Incinerator
Annex II, Provided Any Liquid PCBs Are Drained Prior to Disposal
Decontaminate Per Annex IV

(1) Annex I Incinerator defined in 40 CFR 761.40.
(2) Requirements for other approved incinerators are defined in 40 CFR 761.10(a).
(3) Annex II chemical waste landfills are described in 40 CFR 761.41. Annex II disposal is permitted if the PCB waste analyzes less than 500 ppm PCB and is not ignitable as per 40 CFR Part 761.41(b)(8)(iii).
(4) Disposal of containerized capacitors in Annex II landfills is permitted until March 1, 1981. Thereafter, only Annex I incineration is permitted.

Figure 3. Disposal requirements for PCBs and PCB items. 36

regulations.[35] The minimum operating requirements for disposal of liquid wastes presented in Annex I include:

- 2 second dwell time at 1200°C (2190°F) and 3 percent excess oxygen; or
- 1.5 second dwell time at 1600°C (2910°F) and 2 percent excess oxyger.

The dwell time refers to the residence time of the PCBs in the combustion chamber, while the oxygen content is measured in the stack gas. Additional criteria, including monitoring requirements, approval conditions, and trial burn requirements, are also included in the Annex I citation. These requirements should be referenced directly to resolve any questions.

While the Annex I incinerators were established for liquid PCB wastes, they may also be employed for solid PCB disposal, provided a destruction and removal efficiency of 99.9999 percent is met. Reference 36 provides a complete description of operating principles, advantages and disadvantages and test data for each incinerator design.

Commercial or industrial incinerators that are intended to destroy liquid PCB wastes must demonstrate compliance with the Annex I requirements through a comprehensive trial burn program. As of 1986, four stationary commercial incinerators, eight industrial incinerators and two mobile incinerators were approved as Annex I incinerators under these requirements.[37-40] However, these numbers are subject to change as new approvals are granted, operations are terminated, and so on. The commercial units include those operated by Rollins Environmental Services in Deer Park, Texas; Energy Systems Company (ENSCO) in El Dorado, Arkansas; General Electric Company in Pittsfield, Massachusetts; and SCA in Chicago, Illinois. In addition to approval under the Annex I requirements, Rollins and ENSCO have been approved for solid PCB disposal under the 99.9999 percent destruction requirement.

The industrial PCB incinerators approved under Annex I are operated by the General Electric Company in Waterford, New York; by Dow Chemical in Freeport, Texas; Oster Creek, Texas; and Plaquemine, Louisiana; by Vulcan Materials in Geismar, Louisiana; by PPG in Lake Charles, Louisiana; by LaPort Chemical Corporation in Pasadena, Texas; and by Los Alamos Scientific in Los Alamos,

New Mexico. The Annex I mobile incineration systems are operated by EPA, Edison, New Jersey; and by Pyrotech, Tullahoma, Tennessee. The Annex I mobile systems have been tested and approved to operate in all ten U.S. EPA regions.[40]

Finally, it must be mentioned that municipal sewage sludge incinerators are used to incinerate PCB-containing sludges at certain locations throughout the country. This condition has resulted from the inadvertent PCB contamination of municipal sewer systems resulting from historical PCB disposal. As sludge incinerators are not designed to operate in the temperature ranges specified for the Annex I requirements, they do not insure sufficient destruction of the PCBs. In addition, municipal waste incinerators have been identified as potential PCB emission sources due to their processing of PCB-containing wastes. Sewage sludge and municipal incinerators are discussed later in this section.

Emissions--

Approved Incineration of Liquid PCB Wastes-Published PCB destruction efficiency test data for 11 of the EPA approved Annex I liquid waste incinerators are presented in Table 8. The location and type of incinerator associated with each facility is also presented along with the PCB emission factor that results from applying the stated destruction efficiency on inlet PCB level for each unit. The units for the emission factors are grams of PCB emitted per kilogram of PCB charged (g/kg). As can be seen from the table, these emission factors vary as much as four orders of magnitude. However, this is not reflective of optimum Annex I incinerator performance. Several of these tests were not compliance determinations, but rather research and development efforts, and were not necessarily conducted under optimum conditions. Furthermore, several of the destruction efficiency values were reported to only two significant figures, making it impossible to calculate an emission factor less than 0.1 g/kg. For those test results that were reported to five or six significant figures, the corresponding emission factor is, in most instances, less than 0.001 g/kg. This level is indicative of optimum Annex I performance. The average PCB destruction efficiency for all stationary incinerator test data presented in the table is 99.997. This corresponds to an emission factor of 0.03 g/kg.

TABLE 8. PCB EMISSIONS FROM ANNEX I INCINERATORS BURNING LIQUID WASTES

Facility	Location	Type of incinerator	Type of PCB waste	Destruction and removal efficiency[a]	PCB emissions[a] (g/kg PCB charged)	Reference
Stationary Incinerators						
General Electric Company	Pittsfield, Massachusetts	Liquid injection	Liquids	99.9921-99.9995	0.005-0.079	42
General Electric Company	Waterford, New York	Liquid injection	Liquids	99.99	0.1	41
SCA Chemical Services	Chicago, Illinois	Rotary kiln	Liquids	99.99	0.1	41
SCA Chemical Services	Chicago, Illinois	Rotary kiln	Solids	99.99	0.1	41
Dow Chemical Company	Freeport, Texas	Liquid injection	Liquids	99.99999	0.001	41
Dow Chemical Company	Plaquemine, Louisiana	Liquid injection	Liquids	99.9971	0.029	41
Dow Chemical Company	Oster Creek, Texas	Liquid injection	Liquids	99.999998	0.00002	41

(continued)

TABLE 8. (continued)

Facility	Location	Type of incinerator	Type of PCB waste	Destruction and removal efficiency[a]	PCB emissions[a] (g/kg PCB charged)	Reference
Vulcan Materials	Geismar, Louisiana	Liquid injection	Liquids	99.99998	0.0002	41
LaPort Chemical Corp.	Pasadena, Texas	Liquid injection	Liquids	99.99999	0.0001	41
PPG	Lake Charles, Louisiana	Liquid injection	Liquids	99.99997 99.99998	0.0003 0.0002	41
			Average:	99.997	0.03	
Mobile Incinerators	Home Base					
EPA	Edison, New Jersey	Rotary kiln	Liquids	99.999	0.01	42
Pyrotech(Pyro-Magnetics)	Tullahoma, Tennessee	Rotary kiln	Liquids	99.9999	0.001	39,41

[a]Includes gaseous and particulate emissions, except as where noted. Note: As can be seen from the table, these emission factors vary by more than three orders of magnitude. However, this is not reflective of optimum Annex I incinerator performance. Several of these tests were not compliance determinations, but rather research and development efforts, and they were not necessarily conducted under optimum conditions. Furthermore, several of the destruction efficiency values were reported to only two significant figures, making it impossible to calculate an emission factor less than 0.1 g/kg. For those test results that were reported to five or six significant figures, the corresponding emission factor is, in most instances, less than 0.001 g/kg.

Approved Incineration of Non-Liquid PCB Wastes-Approved incinerators burning non-liquid PCB articles (such as PCB capacitors) have a mass PCB emission limitation of 0.001 g PCB/kg of PCB introduced into the incinerator. This is equivalent to a PCB destruction efficiency of 99.9999 percent and an emission factor of 0.001 g/kg.

Sewage Sludge and Municipal Waste Incineration-While neither approved nor recommended for PCB waste destruction, sewage sludge and municipal waste incinerators have been identified as potential PCB emission sources.[43-46] This can happen when sludge has been contaminated by past industrial discharges of PCBs or when municipal refuse contains miscellaneous PCB-laden trash such as fluorescent light ballast capacitors and carbonless copy paper. While these PCB-containing products are no longer being manufactured, they will continue to appear in waste streams until their economic life has been completed. With time, the quantities of PCB-contaminated sludge and PCB-containing wastes incinerated in municipal incineration facilities should slowly decrease. In addition, the presence of PCBs in these waste streams, especially sewage sludge, is highly site specific, dependent upon local manufacturing and waste discharge characteristics. Therefore, the PCB emission factors presented for these incineration facilities will not necessarily apply to a particular site.

Emission data for sewage sludge incinerators and municipal solid waste refuse incinerators are presented in Tables 9 and 10, respectively. As is clear from these tables, there is very little data on PCB emissions from either of these incinerator types. The New Bedford, Massachusetts and Palo Alto, California sewage sludge incinerator tests were conducted specifically to ascertain the PCB destruction efficiency of these units. Consequently, the PCB destruction efficiency of these units was reported and an emission factor,

TABLE 9. PCB EMISSION FACTORS FOR SEWAGE SLUDGE INCINERATORS

Facility	Year of test	Incinerator design	Destruction efficiency	PCB emission factor[a] (g/kg PCBs)	PCB emissions (ug PCBs/kg sludge)	Reference
Sludges Known to Contain PCBs						
New Bedford, Massachusetts	1977	Multiple hearth	46.3 - 77.5	225 - 537	12 - 36	43
Palo Alto, California	1976	Multiple hearth	91.7 - 97.1	29 - 83	b	44
Detroit, Michigan	1980	Unknown	Unknown	Unknown	58 - 64	45
			Average:	220	43	
Sludges With Unknown PCB Contaminantion[c]						
Wyandotte, Michigan	1980	Unknown	Unknown	Unknown	4.2 - 7.2	45
Akron, Ohio	1980	Unknown	Unknown	Unknown	2.5 - 4.2	45
			Average	--	4.5	

[a]Emission factors in terms of grams PCBs emitted per kilogram of PCBs charged to the incinerator.

[b]PCB added to sludge for test.

[c]These data represent sludges in which the contamination of PCBs prior to testing was unknown or unclear.

TABLE 10. PCB EMISSION FACTORS FOR MUNICIPAL REFUSE INCINERATORS

Facility	Year of test	Incinerator design	Destruction efficiency	PCB emission factor[a] (g/kg PCB)	PCB emission factor (ug PCBs/kg refuse)	Reference
Chicago, Illinois	1976	Unknown	Unknown	Unknown	62	46
Chicago, Illinois	1980	Unknown	Unknown	Unknown	1.8 - 2.7	45
Sheboygan, New Jersey	1980	Unknown	Unknown	Unknown	4.4	45
				Average:	18	

[a]Emission factors in terms of grams PCBs emitted per kilogram of PCBs charged to the incinerator.

in terms of grams PCBs emitted per kilogram PCB charged, can be calculated. These factors are presented in Table 9 and show the poor PCB destruction efficiency that results from use of a sludge incinerator for PCB disposal. As the New Bedford, Massachusetts sludge routinely contains PCBs, it was also possible to calculate a PCB emission factor in terms of grams of PCBs per kg of sludge feed, and this value is presented in the table. For the Palo Alto, California test, PCBs were deliberately added to the sludge, so this sludge feed emission factor does not apply. Three other sewage sludge incinerator test results reported PCB emissions in the stack gas. These tests did not investigate the source of the PCBs, the sludge feed PCB concentration, or the PCB destruction efficiency of the incinerator. They addressed only PCB stack gas emissions and reported these emissions in terms of unit mass of PCBs per unit mass of sludge feed. These emission factors are also reported in Table 9 (shown as micrograms of PCBs per kilogram sludge in the table). Note the order of magnitude discrepancy that exists between the two highest and two lowest emission factors. For those sludge incinerators such as New Bedford and Detroit that are known to be processing PCB contaminated sludge, the emission factor is 43 micrograms per kilogram sludge (ug/kg). However, for the Wyandotte and Akron incinerators, where the source of PCBs is not known, the emission factor is 4.5 ug/kg sludge. Based on this limited data base, it is recommended that the larger emission factor be used when the sludge is known to contain PCBs, while the smaller value should be employed when the presence of PCBs is not known or unclear.

A similar lack of data on PCB emissions exists for municipal refuse incinerators.* Data for three incinerators are presented in Table 10. Averaging test results for the three incinerators gives an overall emission factor of 18 ug PCBs/kg refuse. Stack gas emissions of PCBs from the three incinerators were quantified without determining the incinerator's PCB destruction efficiency. While not stated, it is assumed that the PCBs were

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(*)Data concerning PCBs from municipal refuse incinerators are currently being developed by the Office of Solid Waste under the Agency's comprehensive study of municipal waste combustion.

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contained in certain segments of the trash. This is confirmed by published research findings. The municipal refuse incinerator studied in Chicago in 1976 consisted of four identical furnaces of the water wall type with a reciprocating grate stoker and capacity of 400 tons refuse per incinerator per day.[46] No information was available on design or operation of the other incinerators tested.

As part of a recent study on the PCB emissions from burning of coal/refuse mixtures, the PCB content of various consumer paper products was analyzed.[47] This study indicates that such paper products as magazine covers and paper towels contained up to 139 micrograms of PCB per kilogram of paper (ug/kg). These levels, which were reported in 1981, were attributed to the repeated recycle of waste paper containing PCBs. For example, carbonless copy paper manufactured prior to 1971 contained PCB levels as high as 7 percent. This copy paper then became a component of waste paper which was recycled. The PCBs inevitably were introduced into other paper products, resulting in continued measurable levels in municipal refuse some 4 years after the PCB manufacturing ban was imposed. Refuse derived fuel (RDF) manufactured from these paper products had PCB levels of 8,500 ug/kg, indicating that this fuel is also a source of atmospheric PCBs. Therefore, it must be assumed that municipal refuse does contain detectable levels of PCBs, and that some of these PCBs will enter the atmosphere when the refuse is incinerated.

The average emission factor for these two municipal incinerator sets was 3.3 ug of PCBs emitted per kilogram of refuse. This is approximately equal to the emission factor for sewage sludge incinerators which have no obvious source of PCB contamination. As with sewage sludge incinerator discharges, PCB emissions from municipal incinerators are expected to gradually decrease as the consumer waste products containing PCBs outlive their useful life and are discarded, and as recycled PCB articles constitute an increasingly smaller portion of the incinerator's waste stream.

High Efficiency Boilers

Conventional industrial and utility boilers can be used to destroy PCBs if proper combustion conditions are maintained. These conditions are defined in the regulations, and include:[35]

1. The boiler must be rated at a minimum of 50 million Btu/hour.
2. The concentration of PCBs in PCB-contaminated fluid shall not exceed 500 ppm and the rate of PCB-contaminated fluid flow to the boiler shall not exceed 10 percent of the total fuel feed rate.
3. The waste feed rate to the boiler, the coal and/or oil feed rate and the total of both shall be recorded in regular intervals no greater than 15 minutes apart.
4. The PCB-contaminated fluids shall not be fed to the boiler until it is operating at normal operating temperature.
5. The carbon monoxide (CO) concentration in the stack gas shall not exceed 100 ppm for coal fed units, or 50 ppm for oil or natural gas fired units.
6. The excess oxygen (O_2) in the stack gas shall not be less than 3 percent.
7. CO and O_2 will be monitored in the stack gas continuously when the unit is burning contaminated fluid and will be checked at least once every hour.
8. The fuel flow, CO and O_2 data recorded shall be retained in file for 5 years at the boiler address.
9. Records of the quantity of contaminated fluid burned in the boiler shall be kept on a monthly basis and kept in files at the boiler address for at least 5 years.

EPA has approved 18 high efficiency boilers for PCB disposal based on the criteria listed above.[38] The facilities that operate these boilers are listed in Table 11. It is uncertain, however, how many of these boilers have actually burned PCBs, and the total quantity of the PCB fluids destroyed. This list is subject to change as new approvals are granted, operations are terminated, and so on.

TABLES 11. HIGH EFFICIENCY BOILERS PERMITTED TO BURN PCB LIQUIDS*39,41

Company	Location
Public Service Company of New Hampshire	Merrimac Station, NH
New England Power Company	Salem Harbor Station, MA
Northeast Utilities	Middletown, CT
Baltimore Gas & Electric	Chase, MD
Potomac Electric & Power	Morgantown Station, MD
Carolina Power & Light	Moncure, NC
Duke Power Company	Riverbend Station, NC
Louisville Gas & Electric	Louisville, KY
Tennessee Eastman Co.	Kingsport, TN
TVA - Widow's Creek	Bridgeport, AL
General Motors Corp.	Bay City, MI
Hoosier Energy, Inc.	Bloomington, IN
Illinois Power Co.	Baldwin, IL
Northern States Power Company	Minneapolis, MN
Otter Tail Power Company	Fergus Falls, MN
Otter Tail Power Company	Big Stone, SD
Union Electric Company	St. Louis, MO
Washington Water & Power Company	Spokane, WA

*This list is subject to change as new approvals are granted, operations are terminated, and so on. Also, it is uncertain how many of these boilers have actually burned PCBs.

Emissions--

Of the boilers permitted to burn PCB liquids, six are known to have conducted a PCB destruction efficiency test, even though these tests are not required by EPA's PCB regulations.[38] These six test series results are presented in Table 12. In addition, two PCB destruction efficiency tests are also presented that were conducted on a Florida Power and Light boiler in 1974 and a Continental Can Company boiler in 1976. However, as of 1986, these units were not authorized to destroy PCBs.

Table 12 presents the year of the stack test, the type of primary fuel fired in the boiler, and the reported destruction efficiency. As with the Annex I incinerator test data, the boiler test results have been converted to an equivalent emission factor for this study. The units of this factor are also grams of PCB emitted per kilogram of PCB burned (g/kg).

Testing the PCB destruction efficiency of an industrial or utility boiler presents unique problems because EPA's PCB regulations require that PCB-contaminated fluids to be incinerated contain no more than 500 ppm of PCBs.[35] Furthermore, these contaminated fluids cannot represent more than 10 percent of the total fuel feed to the boiler.[35] Consequently, the total fuel burned by a high efficiency boiler cannot contain more than 50 parts per million (ppm) of PCBs. This ceiling on the PCB concentration fired by a boiler presents a challenge in determining PCB destruction efficiency. In order to ascertain if the boiler is achieving a predetermined destruction efficiency (e.g., 99.9 percent), a set amount of PCB must be captured from the stack gas. However, given current analytical PCB detection limits, and the rate at which stack gas samples can be collected, sampling times in excess of 4 to 6 hours per run are often needed to collect a sufficient sample. For all tests reported in Table 12, with the exception of the Continental Can test series, no PCBs were detected in the stack gas sample. Thus, for the purpose of determining a PCB destruction efficiency, the testing company assumed that PCBs were being emitted at a level identical to the minimum detection limits of the analytical methodology. Comparing this assumed maximum outlet PCB level with the known inlet PCB level in the fuel permits the calculation of an

TABLE 12. PCB HIGH EFFICIENCY BOILER TEST RESULTS

Facility	Date of test	Type of fuel	Destruction efficiency[a,b]	PCB emissions[b] (g/kg)	Reference
Florida Power & Light	1974	Oil	99.9997[a]	0.003	42
Continental Can Company	1976	Oil	99.1 - 99.9[a]	1.0 - 9.0	42
General Motors	1980	Oil	99.99	0.1	48
Northeast Utilities	1981	Oil	99.997	0.03	48
Average for oil-fired boilers			99.8	2.0	
Tennessee Eastman Company	1979	Coal	99.7 - 99.993	0.07 - 3.0	42
Union Electric	1981	Coal	99.95	0.5	48
Duke Power	1981	Coal	99.92	0.8	41
Tennessee Valley Authority	1981	Coal	99.95	0.5	41
Average for Coal-fired boilers			99.9	1.0	

[a]Includes gaseous and particulate emissions.

[b]No actual PCB emissions were detected during sampling. However, the maximum possible PCB emissions level was assumed to be equal to the minimum detection limits of the analyical methodology (0.2 ug/m^3). The destruction efficiencies and emission factors were calculated using this maximum PCB emissions level and fuel/waste PCB concentrations.

estimated minimum PCB destruction efficiency. These destruction efficiencies, as can be seen in the table, are generally limited to 99.99 percent. The existing PCB sampling and analysis methodologies prohibit the determination of higher PCB destruction efficiencies unless either the inlet PCB concentration is increased or the outlet (flue gas) PCB detection sensitivity is increased. These factors account for the destruction efficiency values in excess of 99.99 percent reported in Table 12. The PCB regulations currently limit the waste feed PCB concentration to 500 ppm, effectively capping this option. The PCB sensivitity of flue gas sampling can be increased by utilizing a high volume stack sampling train such as the Source Assessment Sampling System (SASS). This approach was successfully employed for the Northeast Utilities Test Program.

The PCB regulations do not specify a minimum PCB destruction efficiency for high efficiency boilers. Six of the approved boilers cited in Table 12 achieved efficiencies in excess of 99.9 percent. Testing at two of the boilers resulted in ranges of destruction efficiencies with a minimum value below 99.9 percent and a maximum value of 99.9 percent or higher. The emission factor corresponding to a 99.9 percent destruction efficiency (DE) is 1.0 gram per kilogram while a 99.99 percent DE is equivalent to an emission factor of 0.1 grams per kilogram. Averaging the emission factors in Table 12 results in values of 2.0 g PCB/kg PCB burned for oil-fired boilers and 1.0 g PCB/kg PCB burned for coal-fired boilers.

Annex II Landfills

Annex II chemical waste landfills can be used for some, but not all, PCB wastes. Table 13 lists those PCB wastes that can be disposed in this type of treatment facility. The technical requirements for a PCB landfill are set forth in Annex II of the PCB regulations.[35] These requirements address such factors as thickness and permeability of the soil, hydrology, flood protection, topography, ground water monitoring system, leachate collection, landfill operating and supporting facility standards. The reader should refer to Annex II landfill standards to resolve specific questions regarding these

TABLE 13. PCB CONTAMINATED MATERIALS ACCEPTABLE FOR LAND DISPOSAL[49]

Description of PCB type	Eligible for land disposal after January 1, 1980
PCB Mixture Type	
• Nonliquid PCB mixtures in the form of contaminated soil, rags or other solid debris	No
• Soil and solid debris contaminated with PCBs due to a spill or as a result of PCB placement in a disposal site prior to promulgation of final EPA regulations for PCB disposal (April 18, 1978)	Yes
• Dredged materials and municipal sewage sludge that contain PCBs	Yes
PCB Articles	
• Those articles technically infeasible for incineration, such as drained and flushed transformers[a]	Yes
• Sealed capacitors	No
PCB Containers	
• Drained containers	Yes

[a]Written application to EPA is required for landfilling articles other than transformers.

requirements. There are currently ten sites that are approved as Annex II chemical waste landfills. These sites are listed in Table 14. However, this list is subject to change as new approvals are granted, operations are terminated, and so on.

In addition to the currently operating sites, there are several sites throughout the country that have been given permission by the EPA Regional Offices to conduct a one-time disposal of PCB dredge spoils, contaminated debris, etc. It must be recognized that the operating and one-time landfills are known disposal sites of PCBs that have been reviewed and approved by EPA since promulgation of its PCB regulations in 1979. There are, however, many other conventional sanitary landfills, dumps and other unauthorized and as yet unidentified disposal sites where PCBs were disposed prior to enactment of the PCB rules. It is the PCB emissions from these unknown, unauthorized sites that cause a problem in estimating total PCB emissions from landfills and other disposal facilities. This aspect of the PCB emissions estimation procedure will be subsequently discussed.

Emissions--

Estimation of PCB emissions from land disposal facilities, including Annex II landfills, conventional sanitary landfills, and/or abandoned dump sites, is difficult. While data exist on ambient PCB levels in and around landfills,[50] little emission testing has been conducted to quantify mass emission rates of PCBs. Furthermore, to calculate PCB emissions from these sources, several site specific characteristics must be known. These factors include the amount, PCB concentration and location of the contaminated waste, the porosity, organic content and depth of the soil cover employed, and local temperature, wind speed, and precipitation data. If these data are available, then published diffusion equations can be used to calculate landfill emissions.[51] Generally, this information is known for only the newest, most regulated landfill sites - Annex II landfills. However, PCBs disposed of in these landfills are often placed in sealed containers, and PCB emissions from these sources should not be significant, regardless of site specific

TABLE 14. PCB ANNEX II CHEMICAL WASTE LANDFILLS[a],40

Company	Location
CECOS International	Niagara Falls, New York
SCA Chemical Waste Services	Model City, New York.
Chemical Waste Management	Emelle, Alabama
Chemical Security Systems	Arlington, Oregon
Envirosafe Services of Idaho	Mt. Home, Idaho
U.S. Ecology	Beatty, Nevada
Chemical Waste Management	Kettleman City, California
Casmalia Resources	Casmalia, California
CECOS International	Williamsburg, Ohio
U.S. Pollution Control	Oklahoma City, Oklahoma

[a]This list is subject to change as new approvals are granted, operations are terminated, and so on.

conditions. If sufficient data are available to calculate or estimate PCB emissions from individual disposal sites, then a point source emission estimate can be made.

Estimating PCB emissions from landfills is further complicated by the uncertainty regarding the amount and location of PCBs discharged to land disposal facilities prior to 1970. These data are available, in part, for PCB manufacturing facilities, but not for the disposal of PCB-containing products. Given the widespread use of such PCB-containing consumer items as paper containers and fluorescent light ballasts, it must be assumed that every public and commercial landfill site contains PCB products.

Certain aspects of land disposal of PCBs are known. If exposed directly to the atmosphere, a certain portion of the PCBs will be emitted to the atmosphere through volatilization, evaporation, and co-distillation.[52] In addition, PCBs may become adsorbed on fine dust in the soil. This dust may be entrained by wind, or PCB oil itself may form an aerosol in high wind. The specific amount released is dependent upon the PCB isomer, the type of soil in contact with the PCB mixture, and the ambient temperature and windspeed.[53] Published data indicate that the less chlorinated (those with four or fewer chlorine atoms) PCB isomers volatilize faster.[53] These less chlorinated isomers have higher vapor pressures and greater water solubilities and thus demonstrate increased vaporization and are more mobile in the environment.[54,55] Consequently, PCB wastes with a greater proportion of the lower isomers will demonstrate a greater loss to the atmosphere. The type of soil in contact with the PCB waste affects emissions as soils with greater organic content tend to bind the PCBs more strongly, while soils with little or no organic content (e.g., sand) lose PCBs through evaporation rapidly.[56] This is demonstrated graphically in Figure 4 with the amount of PCB evaporating varying greatly, depending on the type of soil. Virtually all of the PCBs are evaporated from sand, while less than 10 percent was evaporated from topsoil rich in organic matter.

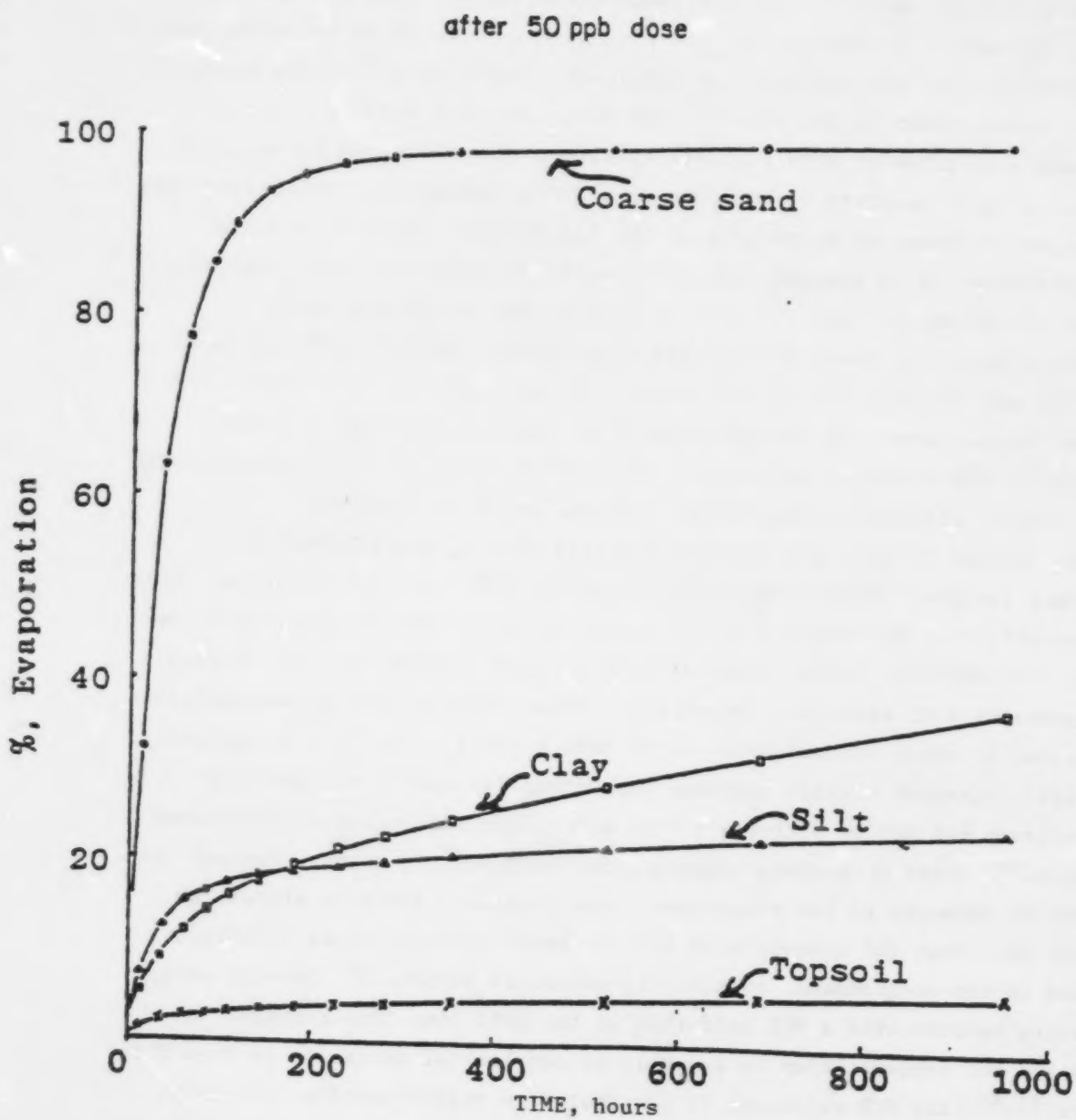


Figure 4. Evaporative loss of ^{14}C-Aroclor 1242.[63]

Since the vapor pressure of all PCB mixtures (Aroclors) increases with temperature,[57] the rate of PCB volatilization also increases with temperature. In addition, studies have shown that the volatilization will increase with wind speed.[58] One published PCB emission study attempted to quantify the effect of temperature and wind speed. This study was undertaken in conjunction with the dredging and subsequent land disposal of PCB sediments from the Hudson River in New York.[53] PCB emissions from landfills without covers and dump sites at this disposal operation were estimated to be 3,000 lb/yr for a total quantity of 700,000 lbs of PCBs landfilled. This translates to an emission factor of 4.286 g/kg of PCB landfilled. While this was an annual estimate, it is assumed that it is valid for only the first year after PCBs are placed on the land. Within this year, the relatively rapid volatilization of the lower PCB isomers would occur, the soil effects would be exhibited, and the seasonal variations in PCB emissions due to weather effects would be demonstrated. No estimate was given for the decrease of these emissions in the second or subsequent years after disposal of the contaminated dredge spoils, although a significant decrease would be expected.

PCBs covered by soil in a managed landfill setting are affected by additional factors. Soils slow diffusion of the PCBs to the atmosphere. This is especially true for finely divided soils and those with a higher moisture content. In addition, cover material with a higher organic content or with a lower porosity will also limit emissions. PCBs buried in the ground may also be affected by other factors which would affect their volatility and emission potential. Research studies indicate that microbial action and chemical decomposition may act on soil-based PCBs and reduce them to less chlorinated compounds.[59] These by-product compounds may subsequently migrate through the soil and be released to the atmosphere. One published estimate states "we conclude that most PCB isomers with four or fewer chlorine atoms have been degraded in the environment, possibly by microbial action."[60] Several other literature sources cite a PCB half-life in the soil (the time required to reduce the PCB concentration to one-half of its initial value) to be from 5 to 6 years.[61,62] The PCB reduction is attributed to volatilization, microbial action and/or chemical decomposition. These estimates remain to be proven in the field and are possibly contradicted by other published data. Two recent

studies conducted following spills of PCB liquids noted no change in soil based PCB levels, even 2 years after the initial spill.[63,64] It is not known if the same PCBs were encountered in all these studies. This PCB reduction mechanism requires additional research.

Only one published reference estimated PCB mass emissions from landfills.[65] This study reported the results of sampling at seven different municipal landfills. Six of these samples were obtained in 1981 and they indicated an average PCB emission of 190 nanograms (190×10^{-9} g) of PCB per cubic meter of methane gas generated. The study stated that "based on an estimate that municipal landfills generate 2×10^{12} ft^3/yr of methane nationwide, the results found in this project indicate that such landfills contribute about 18 kg/yr of PCBs to the atmosphere."[65]

The many site specific and unknown factors involved with calculating PCB emission rates from landfills make determination of a generally applicable PCB emission factor for this source category difficult.*

Other Approved Disposal Methods

Thermal Method--

In addition to incinerators and boilers, the EPA Regional Administrators are given authorization by the PCB regulations to approve other thermal destruction techniques if these processes can effect destruction of PCBs equivalent to that of incinerators or boilers. The only technology to gain such an approval to date is the pyrolysis process operated by the Huber Corporation in Borger, Texas. This system will treat contaminated soils.

(*)Information related to emissions of toxic compounds from landfills is currently under development by the Emission Standards and Engineering Division of the Office of Air Quality Planning and Standards under the Agency's comprehensive study of hazardous waste treatment, storage, and disposal facilities.

Several thermal technologies, however, have received short duration (6 month) approval to conduct research and development projects. These include such diverse projects as use of a fluid wall reactor, a cement kiln, a diesel engine, a steam stripping operation, an aluminum melting furnace and a molten salt process.[41]

Chemical Dechlorination and Other Nonthermal Methods--

The PCB regulations also give the EPA Regional Administrators the authority to approve nonthermal PCB disposal methods if they achieve a PCB disposal/destruction equivalent to that of an Annex I incinerator. This mechanism has been used by 11 companies nationwide to gain commercial scale approval of their chemical dechlorination disposal processes.

Chemical dechlorination processes use chemical reagents to break apart the extremely stable PCB molecule, rearranging it to form other chemical compounds that are considered harmless and environmentally safe. These processes destroy the PCB molecule but do not break down the biphenyl structure of the molecule. Only the chlorine atoms which give the PCB molecule chemical and biological stability are removed.

Most chemical dechlorination processes use a sodium reagent to strip away the chlorine atoms from the PCB molecule. The wastes generated from the process are sodium chloride and nonhalogenated polyphenyls. The exact constituents of the polyphenyls are often not known, but indications show that the sodium chloride and polyphenyls can be disposed of safely.[66]

Most applications involve destruction of PCBs that contaminate otherwise valuable oil. The sodium dechlorination processes can be run at ambient or moderate temperature and, although they chemically destroy the PCBs contained in oil, they do not destroy the oil itself. Therefore, the oil can be recycled for reuse. Sodium dechlorination is limited in that it is only capable of economically dechlorinating PCBs in otherwise valuable oil.

Dechlorination of PCBs by sodium reagents must be conducted in nitrogen or similarly inert atmospheres to prevent excessive reagent consumption and fire hazard due to the hydrogen generation on contact with any water or moisture present in the oil.[66] These dechlorination processes are significant because they are widely used commercial scale technologies that offer the additional benefit of being mobile. They are currently employed for the decontamination of mineral oil dielectric fluids from transformers, although additional research is being conducted on other PCB wastes as well.

Other nonthermal PCB treatment technologies that have been investigated or actually approved for commercial scale PCB disposal include physical/chemical extraction techniques and biological reduction methods. The physical/chemical techniques extract the PCBs from transformers or capacitors and concentrate them for disposal. They do not destroy the PCBs. Four companies are currently permitted by EPA to extract the contained PCBs using these physical/chemical methods. These companies are Quadrex HPS, Inc. in Gainesville, Florida; Environmental International Electrical Services, Inc. in Kansas City, Kansas; Rose Chemical in Kansas City, Missouri; and PCB Treatment, Inc. in Kansas City, Missouri.[40] Quadrex has been approved for operation in all ten U.S. EPA regions.[40]

Many bench scale studies have investigated the biodegradability of PCBs. The PCB concentrations used in these tests have ranged from a few ppb to 1,000 ppm. In general, these studies have shown that biodegradation can occur, but the residence times are long and the actual rate of degradation is dependent on the specific PCB isomer and its chlorine content.[67] While not a principal commercial disposal technique or emission source at this time, biodegradability of PCBs may possibly be used to a greater extent in the future, especially with regard to spills cleanup. A commercial scale biodegradation approval has been issued by EPA Region VI to Detox, Inc. of Houston, Texas for the treatment of PCB contaminated soils and sludges although the process is not yet operational.[40,68]

Emissions--The 13 companies that are currently approved for chemical dechlorination of PCB fluids are presented in Table 15. The PCB concentration of the waste stream treated by each dechlorination technology is presented in the table. Because each technology was required to treat the contaminated fluids until an outlet PCB concentration of less than 2 ppm was achieved, the PCB destruction efficiency of each system can be calculated using the known input concentration and the 2 ppm value as a maximum outlet value. These destruction efficiency values are also shown on the table, together with an emission factor which is based on this destruction efficiency. The emission factor is in units of micrograms of PCBs released per kilogram of PCB treated.

Until April 1983, approval of these dechlorination methods was issued by EPA Regional Offices using a phased approval. A company typically applied for approval to dechlorinate PCBs at a specified level, e.g., 1,000 ppm. It was then tested to demonstrate destruction of PCBs to below 2 ppm (the generally accepted PCB detection limits for this technology). Certain dechlorination technologies require that the contaminated PCB fluids be recycled several times through the process in order to meet this 2 ppm outlet level. Upon successful demonstration of PCB removal, the technology was approved with such items as the maximum processing rate, the maximum inlet PCB concentration and the recycling rate specified in the approval. If the company subsequently requested approval to decontaminate fluids at a higher PCB level, it was required to conduct another PCB destruction efficiency test in the region handling the application. This test series was conducted in one EPA region and the resulting test data were usually accepted by all other regions.

Subsequent to April 29, 1983, all PCB disposal technologies (nonthermal and thermal alike) that are to be used in more than one EPA Region have to be approved by EPA Headquarters. Their approval procedure is expected to be similar to that previously outlined.

TABLE 15. PCB EMISSION FACTORS FOR CHEMICAL DECHLORINATION METHODS [a,37,40,41]

Company	Location	Inlet PCB concentration[b] (ppm)	Outlet PCB concentration (ppm)	PCB destruction efficiency[c]	PCB emission factor[d] (ug/kg)
Sunohio	Canton, OH[e]	2,500 - 4,500	<2	99.92 - 99.96	0.44 - 0.80
Acurex	Mountain View, CA[e]	7,500	<2	99.97	0.30
PPM	Tucker, GA[e]	1,100	<2	99.82	1.8
Transformer Consultants	Akron, OH[e]	5,000 - 10,000	<2	99.96	0.40
Franklin Institutes	Philadelphia, PA	7,406	<2	99.97	0.30
General Electric	Schenectady, NY	1,050	<2	99.81	1.9
Rose Chemical Company	Kansas City, MO	10,000	CBI[f]	CBI	--
T & R Electric	Coleman, SD	500	N/A[g]	N/A	--
Chemical Decontamination Corp.	Birdsboro, PA[e]	650	<2	99.60	4.0
Environmental International	Kansas City, KS	N/A	N/A	N/A	--
Environmental Resources Mgmt.	North Kansas City, MO	N/A	N/A	N/A	--
Exceltech, Inc.	Freemont, CA	N/A	N/A	N/A	--
Trinity Chemical Co.	Shawnee Mission, KS	N/A	N/A	N/A	--

[a]This list is subject to change as new facilities are approved, operations are terminated, and so on.

[b]Approved inlet concentration varies with EPA Region.

[c]Calculated using a maximum outlet value of 2 ppm.

[d]Emission factors in units of micrograms of PCBs released per kilogram of PCB treated.

[e]Facility is approved to operate in all ten U.S. EPA regions.

[f]CBI - Confidential Business Information.

[g]Not available.

Since all chemical dechlorination techniques require that the outlet PCB level be less than 2 ppm, the calculated PCB destruction efficiency is dependent upon the inlet PCB level. As shown in Table 15, these inlet PCB levels vary from 500 to 10,000 ppm, depending on the technology used. Consequently, the reported PCB destruction efficiencies range from 99.60 to 99.97. The PCB emission factors corresponding to these destruction efficiencies range from 4.0 to 0.3 g of PCBs emitted per kilogram of PCB processed.

ACCIDENTAL RELEASES

Description

In addition to the principal point and area sources previously discussed, incidental emissions of PCBs may result from intermittent, accidental releases such as spills, leaks, fires, etc. These accidental PCB discharges may enter the atmosphere through failure and subsequent rupture of an existing piece of PCB equipment or through an accident (e.g., fire) to a piece of PCB equipment in service. Both of these sources of PCB releases can be estimated on a national basis.

The PCBs that remain in active service at this time are those contained in "closed systems", i.e., those pieces of electrical equipment that completely enclose the PCBs and do not provide direct atmospheric access of the PCBs during normal use. This equipment includes PCB transformers, capacitors, voltage regulators, circuit breakers, and reclosures. The number of each of these items, the pounds of PCBs they contain, and the estimate of annual pounds of PCBs leaked and/or spilled was investigated by the Edison Electric Institute and by the Utility Solid Wastes Activity Group (EEI/USWAG) for EPA.[69] These data were subsequently reported in the April 22, 1982 Federal Register relative to a proposed modification to the PCB regulations.[70] These Federal Register data are presented in Tables 16 and 17. An additional column was added to Table 17 to update utility PCB spills/leaks to cover the entire population of electrical equipment including that owned by industrial firms. These tables indicate that over 99 percent of the total quantity of PCBs

TABLE 16. ESTIMATED PCB LEAKAGE/SPILLAGE FROM UTILITY INDUSTRY CLOSED SYSTEMS EQUIPMENT 70

	Number of units in utility industry	Percentage of units containing 50 ppm or greater PCBs	Percentage of units containing 500 ppm or greater PCBs	Total pounds of PCBs	Percentage of total pounds	Upper bound estimate of annual pounds of PCBs leaked/spilled
PCB transformers (Askarel)	39,640	100	100	74,597,283	45.92	20,448[a]
Large PCB capacitors	2,800,619	100	100	87,552,960	53.90	369,251
Mineral oil transformers	20,227,428	11.8	1.1	262,230	0.16	826
Mineral voltage regulators	145,159	14.0	1.7	6,707	0.01	5
Mineral oil switches	385,768	14.0	0	329	0.01	80[b]
Mineral oil circuit breakers	180,939	1.8	0	12,685	0.01	51
Mineral oil reclosers	170,158	0	0	410	0.01	7[b]
Mineral oil electromagnets	76	--	--	0.64[c]	0.01	--
Mineral oil cable	6,545 miles	--	--	2,311[c]	0.01	--

[a]Assumes moderate leakage rates equal to mineral oil transformers.

[b]Assumes moderate leakage rates equal to mineral oil circuit breakers.

[c]Assumes an average PCB concentration of 10 ppm.

Note: Dashes indicate no data available.

TABLE 17. ESTIMATED PCB LEAKAGE/SPILLAGE FROM ALL CLOSED SYSTEMS EQUIPMENT (UTILITY AND NONUTILITY) 70

	Percentage of equipment owned by utility industry	Percentage of equipment owned by non-utility industry	Estimated total number of units	Upper bound estimate of annual pounds of PCBs leaked/spilled based on total equipment population
PCB transformers (Askarel)	30[a]	70	132,133	68,160
Large PCB capacitors	85[b]	15	3,294,846	434,413
Mineral oil transformers	80[a]	20	25,284,285	1,033
Mineral voltage regulators	85[c]	15	170,775	6
Mineral oil circuit breakers	85[c]	15	212,869	60
Mineral oil reclosers	85[c]	15	200,186	8
Mineral oil cable	85[c]	15	7,700 miles	--
PCB electromagnets	1	99	200	--
Mineral oil electromagnets	1[d]	99[d]	7,600	--
Small PCB capacitors	e	e	500,000,000[f]	--

[a]Source: Microeconomic Impacts of the Proposed "PCB Ban Regulations", Versar, Inc., 1978.

[b]As reported by the National Electrical Manufacturers Association and referenced in the EEI/USWAG study.

[c]Assumes a distribution equal to that for large PCB capacitors.

[d]Assumes that electric utility industry rarely uses electromagnets.

[e]Small capacitors are used by industry and by consumers. EPA has no information indicating that distribution.

[f]Assumes 870 million existed in 1977 and 10 percent are removed from service annually, due to equipment or appliance obsolescence and capacitor failure.

Note: Dashes indicate no data available.

currently contained in electrical equipment are found in PCB transformers (those containing > 500 ppm of PCBs) and large PCB capacitors (those containing > 3 lbs of PCBs). The following discussion will, therefore, concentrate on these items, although it is applicable to all PCB equipment.

PCB transformers have an estimated operating life of 40 years,[19] while the life span of PCB capacitors is estimated at 20 years.[22] Until this equipment lives out its useful operating life and is eventually retired and replaced with a non-PCB substitute, it will pose a potential threat of PCB emissions from leaks and/or spills. Leaks/spills typically occur in transformers when the gasket joining the top to the body corrodes, tears, or physically fails. PCBs can then leak past this failed section and potentially spill onto the surrounding ground. PCB capacitors typically fail by rupturing, exposing the contained PCBs to the environment. This is due to environmental and weathering effects (e.g., lightning) or material failures (e.g., metal fatigue).

One additional intermittent source of PCBs that was investigated concerned fires involving PCB equipment. Transformer and capacitor fires are infrequent, but when they occur, they can release PCBs as well as toxic incomplete combustion byproducts such as dioxins and dibenzofurans.[71,72] Transformer fires have especially gained widespread attention recently due to the elevated PCB contamination levels that resulted from fires in the interior of buildings in Binghampton, New York and San Francisco, California.

Emissions--

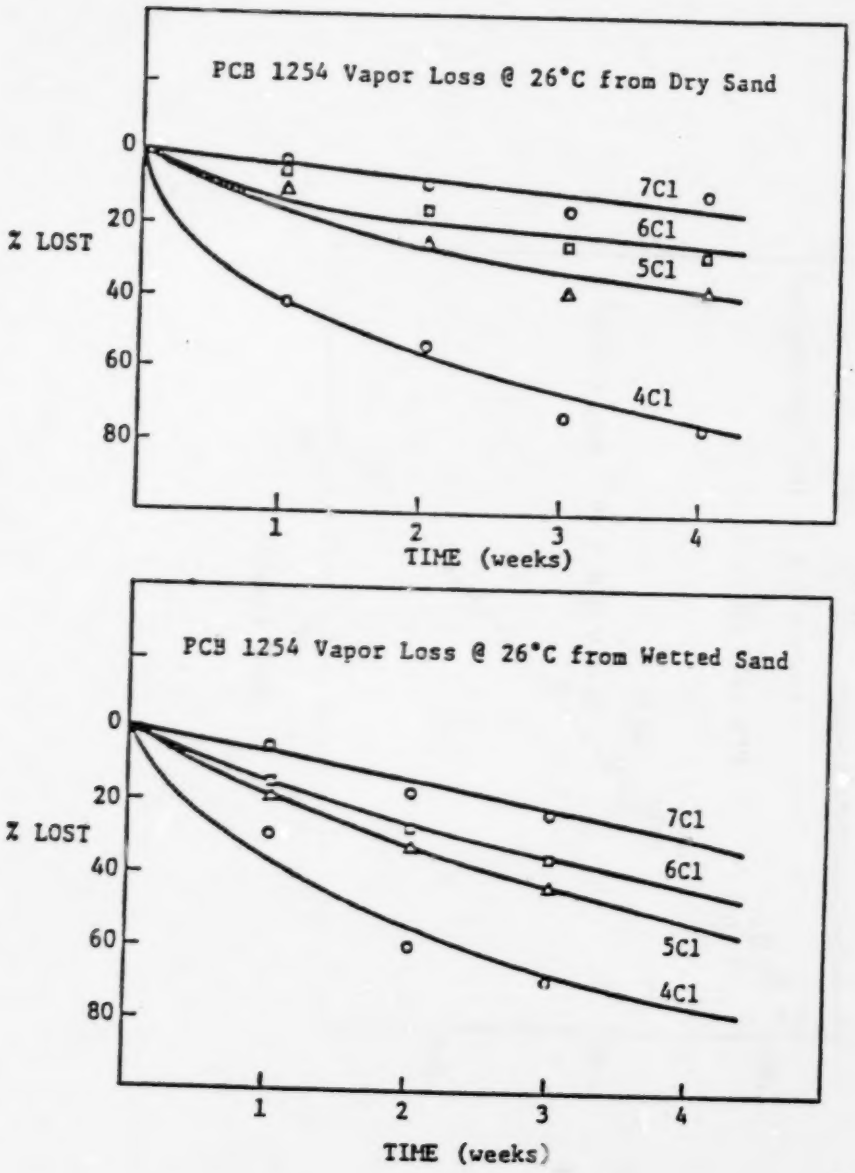
The EEI/USWAG report estimated that the average quantity of PCBs spilled when a PCB transformer leaks or spills varies from 0.56 to 64.5 pounds per incident, while the spill/leak rate for capacitors is 2.0 to 17.1 pounds per incident.[73] These data translate into the annual leak/spill quantities cited in Table 17. When these data are proportioned to account for non-utility (industrial) equipment as well, the total amount of PCBs spilled/leaked is estimated at 503,680 pounds, as indicated in Table 17. This is an upper-bound

estimate of the potential PCBs released and, as such, does not take into account spill cleanup procedures which are designed to remove, contain, and dispose of fluid that has leaked or spilled.

The proportion of spilled PCB that enters the atmosphere will depend on the surface onto which the PCBs are spilled (concrete, soil), the PCB isomers that are spilled, the ambient temperature and windspeed, and the cleanup schedule. As discussed for landfills, PCBs will evaporate and volatilize more rapidly from a nonporous surface such as cement or sandy soil, than they will from an organic rich topsoil. Also, in dry conditions or high winds, PCBs may become entrained either as an aerosol or by being adsorbed on fine soil particles that are subject to entrainment.

Due to their nonflammability characteristics, PCB transformers are typically installed as safety precaution in urban settings where the consequences of a transformer fire would be most severe. These installations include schools, hospitals and office buildings. Consequently, it can be assumed that the average PCB unit is mounted on a solid base. This would enhance vaporization potential in the event of a leak or spill. In addition, PCB transformers and capacitors have historically used Aroclors 1242, 1254, and 1016.[8] The 1242 and 1016 mixtures contain up to 90 percent by weight of the lower isomer PCBs (less than four chlorine atoms), while Aroclor 1254 contains only 20 percent by weight of the lower isomer PCBs.[74] These lower isomers are more likely to be evaporated from an impervious surface. This is shown graphically in Figures 5 and 6. For both wet and dry sand, up to 80 percent of the PCBs are lost to the atmosphere within 4 weeks of the spill. These results indicate that for Aroclors 1016 and 1242, a majority of the spilled PCBs may be volatilized if the contaminated surface beneath the transformer or capacitor is sand or concrete and cleanup is not prompt. However, volatilization in actual field conditions may be less because of removal by other mechanisms such as run-off, percolation, and so on.

Temperature also plays an important role in the amount of PCB evaporated from a spill because of the increase in vapor pressure that occurs with increasing temperature.[75] Figure 7 shows the variation in volatilization rates for temperatures of 26°C (79°F) and 60°C (140°F).



Figures 5 and 6. Volatilization of PCB isomers from Ottawa Sand contaminated with Aroclor 1254.[75]

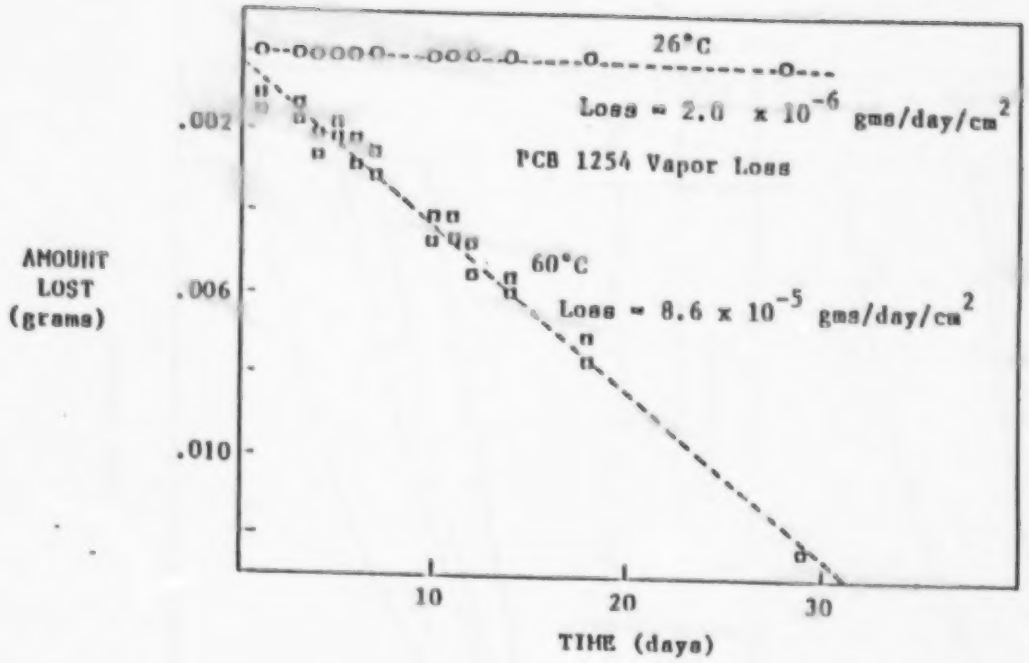


Figure 7. Surface volatilization of Aroclor 1254 from itself as a function of time.[75]

Finally, the rapidity with which spills are cleaned up will affect the amount discharged to the atmosphere. Final EPA regulations affecting PCB electrical equipment require quarterly inspections of PCB transformers, but no mandatory inspections for PCB capacitors.[76] The purpose of the inspections is to minimize environmental releases that result from spills and leaks. However, the utility industry has stated[77] that a large failure of a PCB transformer or capacitor would cause a service interruption and this would be addressed immediately, so the quarterly inspection is not necessarily an accurate indicator of the response time required for cleanup of a spill or leak. No estimate of the average response time for a PCB leak was found in the literature.

The number and diversity of factors affecting PCB emissions from spills and leaks makes estimation of an emission factor difficult. Immediate cleanup of a transformer spill that occurs in New England in mid-winter may result in a negligible release of PCBs, while a continuous leak that occurs in the middle of the summer in the southwest may lead to a substantial PCB release. Each case should be treated individually. Emissions from spilled PCBs are somewhat analagous to those from uncovered dredge spoils. Although the emission factor for dredge spoils is only a very rough approximation, it can be applied to PCB spills in lieu of additional data. An estimated PCB emission rate of 4.286 g/l of landfilled PCBs was reported for the dredge spoils cleanup project in New York (see Emissions from Annex II Landfills).

For fires involving PCB transformers or capacitors, the amount of PCBs released is dependent upon the extensiveness of the fire and the speed at which it is extinguished. A number of these fires have been documented. A New York fire involving 200 gallons of transformer fluid containing some 65 percent by weight PCBs resulted in a release of up to 1,300 pounds of PCBs.[78] A capacitor fire which burned uncontrolled for two hours in Sweden resulted in the destruction of 12 large utility capacitors containing an estimated 25 pounds of PCBs each, for a total potential release of 300 pounds. However, data are incomplete on the exact amount of PCBs released as a result of these two fires.

An ongoing EPA investigation into the annual number of PCB transformer fires sets this figure at approximately 20 per year.[79] The number of PCB capacitor fires is unknown. As these PCB items reach the ends of their economic lives or are retired due to premature failure, their susceptibility to fires will be eliminated and the overall number of PCB transformer and capacitor fires will be reduced.

SECTION 5
SOURCE TEST PROCEDURES

PCB emissions from industrial, sewage sludge, and municipal refuse incinerators can be measured using a modification of EPA Reference Method 5.[80] This method begins with a sample of gaseous and particulate PCBs being withdrawn isokinetically from the source through a series of four impingers with a Florisil absorbent tube between the third and fourth impinger, as shown in Figure 8.

The first and second impingers are of the Greenburg-Smith design. The final two impingers are of the Greenburg-Smith design modified by replacing the tip with a 1.3 cm (1/2 inch) ID glass tube extending to 1.3 cm from the bottom of the flask. The absorbent tube has a 2.2 cm inner diameter, is at least 10 cm long, and has four deep indentions on the inlet end to aid in retaining the absorbent. Ground glass caps are used to seal the absorbent-filled tube prior to and following sampling. The Florisil is activated by heating to 650°C for 2 hours in a muffle furnace. After allowing to cool to near 110°C, the clean, active Florisil should be transferred to a clean, hexane-washed glass jar, sealed with a TFE®-lined lid, and stored at 110°C, until taken to the field for use. If the Florisil is stored more than 1 month it must be reactivated before use.[80]

In assembling the sampling train, sealant greases should not be used. Place 200 ml of water in each of the first two impingers and leave the third empty. If the preliminary moisture determination shows that the stack gases are saturated or supersaturated, one or two additional empty impingers should be added to the train between the third impinger and the Florisil tube. Place 200 to 300 grams or more of silica gel in the last impinger. Weigh each impinger and record the weights. Crushed ice is placed around the impingers after the sample train is assembled.[80]

The sample is collected by pumping air through the sampling train. At the end of the sampling run, the probe is removed from the stack and proper cleanup procedures are followed. The first three impingers are removed, the outsides are wiped off, and the weights are recorded.[80]

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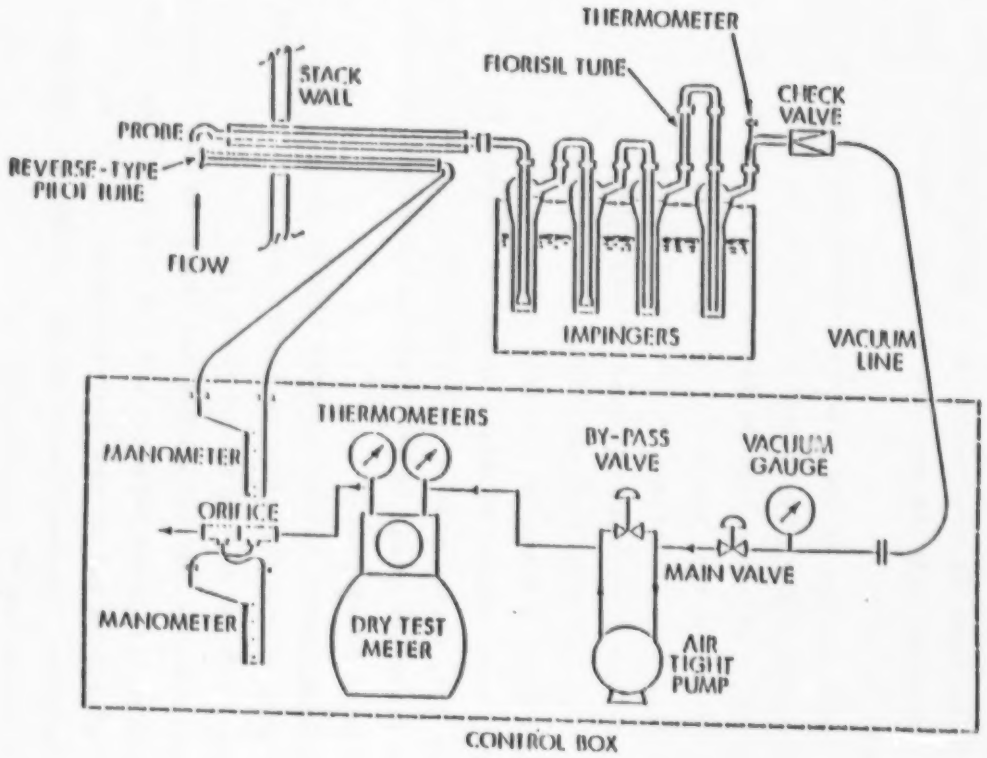

Figure 8. Method 5 sampling train modified for the measurement of PCBs from incinerators. 80

The sample is extracted from the impingers and absorbent tube. The extract is dried and cleaned and is then perchlorinated with antimony pentachloride. Hexane is added to the reaction mixture to remove the residual antimony pentachloride. The solution is allowed to separate into layers and the upper layer is filtered through a column of anhydrous sodium sulfate.[80]

The filtered sample is then assayed for decachlorobiphenyl (DCB) by gas chromatography (GC). The recommended GC column is 2 mm ID by 1.8 m glass packed with 3 percent OV-210 on 100/120 mesh inert support such as supercoport®. The GC should be fitted with an electron capture detector capable of operation at 300°C. Column temperature and carrier gas flow parameters of 240°C and 30 ml/minute are typically appropriate.[80]

The peak area corresponding to the retention time of DCB is measured and compared to peak areas for a set of standard DCB solutions to determine the DCB concentration. The concentrations of the standard solutions should allow fairly close comparison with DCB in the sample extracts. Standard concentrations of 25 to 50 picograms/microliter may be appropriate.[80]

REFERENCES

1. Polychlorinated Biphenyls. National Research Council, National Academy of Sciences, Washington, D.C., 1979. pp. 1-2.

2. Durfee, R.L., et al. PCBs in the United States - Industrial Use and Environmental Distributions. U.S. Environmental Protection Agency, Washington, D.C. Publication No. EPA 560/6-76-005, February 1976. pp. 35-36.

3. Reference 1, pp. 144-145.

4. Reference 1, p. 153.

5. Reference 2, p. 47.

6. Reference 2, p. 1.

7. Encyclopedia of Chemical Technology, 3rd Edition, Volume 5. Wiley Interscience Publication, New York, NY, 1979. pp. 844-846.

8. Hutzinger, O., Safe, S., and V. Zitko. The Chemistry of PCBs. CRC Press, Cleveland, Ohio, 1974. pp. 7-12.

9. Letter from Alice Mayer, Chemical Manufacturers Association to David Misenheimer, GCA/Technology Division providing data on physical properties of Aroclors. January 23, 1986.

10. Reference 1, pp. 150-151.

11. Reference 1, p. 154.

12. Reference 1, pp. 159-160.

13. NRECA PCB Equipment Operations and Management Manual. National Rural Electric Cooperative Association, Washington, D.C., March 1983. p. 6.

14. EPA's Final PCB Ban Rule: Over 100 Questions and Answers to Help You Meet These Requirements. U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, D.C., June 1979. pp. 2-8.

15. Reference 1, p. 147.

16. Reference 1, p. 14.

17. PCBs and the Environment, COM-72-10419, Interdepartmental Task Force on PCBs, Department of Agriculture, March 1972, p. 52.

18. Fuller, B., Gordon, J., and M. Kornreich. Environmental Assessment of PCBs in the Atmosphere. EPA 450/3-77-045, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, November 1977, p. 4-20.

19. Disposal of Polychlorinated Biphenyls (PCBs) and PCB Contaminated Materials, Volume 1. EPRI FP-1207, Electric Power Research Institute, Palo Alto, California, October 1979, p. 3-3.

20. Reference 18, p. 4-21.

21. Cantos, G., Durfee, R.L., Hackman III, E.E., and K. Price. Assessment of Wastewater Management, Treatment Technology and Associated Costs for Abatement of PCBs Concentrations in Industrial Effluents. EPA 560/6-76-006, U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, D.C., January 30, 1976, pp. 32-34.

22. Reference 19, p. 3-6.

23. Reference 8, p. 9.

24. Reference 18, pp. 4-12 to 4-13.

25. Reference 17, p. 54.

26. Reference 17, p. 59.

27. Reference 17, p. 58.

28. Reference 18, pp. 4-9, 4-18.

29. Reference 17, p. 62.

30. Reference 17, p. 64.

31. Reference 17, p. 65.

32. Reference 18, p. 4-34.

33. TSCA Chemical-In-Progress Bulletin, U.S. Environmental Protection Agency, Office of Pesticide and Toxic Substances, Washington, D.C. Vol. 5, No. 4, September 1984.

34. Reference 18, p. 1-8.

35. Polychlorinated Biphenyls (PCBs), Manufacturing, Processing, Distribution in Commerce and Use Prohibitions, 40 CFR Part 761, Federal Register, Volume 44, No. 106, May 31, 1979, pp. 31514-31568.

36. Ackerman, D.G., et al. Guidelines for the Disposal of PCBs and PCB Items by Thermal Destruction. EPA 600/2-81-022, U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina, February 1981, p. 7.

37. Letter from Ed Cohen, EPA Region III Hazardous Waste Management Division to Tom Lahre, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. February 7, 1985

38. McInnes, R.G., and R.C. Adams. Provision of Technical Assistance to Support Implementation of the PCB Regulations (January - December 1983), U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C., May 1984.

39. Telephone conversation between Joan Juzitis, EPA Region I Air and Hazardous Materials Division and David Misenheimer, GCA/Technology Division, February 4, 1986.

40. Information on PCB disposal companies sent by John Smith, Office of Toxic Substances, U.S. Environmental Protection Agency to David Misenheimer, GCA/Technology Division, January 31, 1986.

41. Reference 38, Appendices C and D.

42. Reference 36, p. 55.

43. Piispanen, W., Cass, R.W., Bradway, R.M., and A.S. Werner. PCB Compounds Emanating from the New Bedford Municipal Sewage Sludge Incinerator, Final Report Prepared by GCA/Technology Division, Bedford, Massachusetts. EPA Contract No. 68-01-3154, Task Order No. 24, September 1977.

44. Whitmore, F.C. Destruction of Polychlorinated Biphenyls in Sewage Sludge During Incineration, Final Report Prepared by Versar, Inc., Springfield, Virginia for U.S. Environmental Protection Agency, Washington, D.C. EPA Contract No. 68-01-1587.

45. Murphy, T.J., et al. PCB Emissions to the Atmosphere from Municipal Landfills and Incinerators, Paper presented before The American Chemical Society, Division of Environmental Chemistry, Kansas City, Missouri, September 1980.

46. Petkus, E.J., G.S. Kimura, and W.T. Throp. Polychlorinated Biphenyl Emissions from a Municipal Incinerator. Paper presented at 70th Meeting of the Air Pollution Control Association, Toronto, Canada, June 1977.

47. Richard, J.J., and G.A. Junk. Polychlorinated Biphenyls in Effluents from Combustion of Coal/Refuse, Environmental Science and Technology, Vol. 15, No. 9, September 1981. pp. 1095-1100.

48. Hunt, G.T., Wolf, P., and P.F. Fennelly. Incineration of Polychlorinated Biphenyls in High Efficiency Boilers: A Viable Disposal Option, Environmental Science and Technology, Vol. 18, No. 3, 1984. pp. 171-179.

49. Reference 19, p. 7-6.

50. MacLeod, K.E. Sources of Emissions of Polchlorinated Biphenyls into the Ambient Atmosphere and Indoor Air. EPA 600/4-79-022, U.S. Environmental Protection Agency, Health Effects Research Laboratory, Research Triangle Park, North Carolina, March 1979. p. 38.

51. Shen, Dr. T.T. Estimating Hazardous Air Emissions from Disposal Sites, Pollution Engineering, Vol. 13, No. 8, August 1981. pp. 31-34.

52. Reference 18, pp. 4-35.

53. Tofflemire, T.J., Eng, D., and T.S. Shen. Volatilization of PCB from Sediment and Water: Experimental and Field Data Proceedings of the Mid-Atlantic Industrial Waste Conference, Pennsylvania State University, July 15-17, 1979. pp. 100-109.

54. Nisbet, I.C., and A.F. Sarofim. Rates and Routes of Transport of PCBs in the Environment, Environmental Health Perspectives, Volume 1, April 1972, pp. 25-27.

55. Reference 8, pp. 10-17.

56. Reference 53, p. 9.

57. Reference 53, p. 27.

58. Reference 53, p. 30.

59. Destruction Technologies for Polychlorinated Biphenyls, Environment Canada, Waste Management Branch, Toronto, Canada, 1982. p. 76.

60. Reference 54, p. 29.

61. Reference 18, pp. 1-16.

62. McClure, V.E. Transport of Heavy Chlorinated Hydrocarbons in the Atmosphere, Environmental Science and Technology, Vol. 10, No. 13, December 1976. pp. 1223-1229.

63. Follow-up Study of the Distribution and Fate of Polychlorinated Biphenyls and Benzenes in Soil and Ground Water Samples After an Accidental Spill of Transformer Fluid. EPA 904/9-76-014, U.S. Environmental Protection Agency, Atlanta, Georgia, January 1976. p. 1.

64. Reference 19, p. 7-1.

65. Reference 45, p. 208.

66. Reference 56, p. 48.

67. McInnes, R.G., and R.J. Johnson. Provision of Technical Assistance to Support Implementation of the PCB Regulations (January - December 1982), U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C., May 1983, Appendix G.

68. Letter from Judy Gordon, Office of Solid Waste, U.S. Environmental Protection Agency to Tom Lahre, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. February 4, 1985.

69. Comments and Studies on the Use of Polychlorinated Biphenyls in Response to an Order of the U.S. Court of Appeals for the District of Columbia Circuit, Submitted by the Utility Solids Waste Activities Group, the Edison Electric Institute, and the National Rural Electric Cooperative Association, February 12, 1982.

70. Polychlorinated Biphenyls (PCBs); Use in Electrical Equipment; Proposed Rules, 40 CFR Part 761, Federal Register, Vol. 47, No. 78, April 22, 1982. pp. 17426-17446.

71. Jansson, B., and G. Sundstrom. Formation of Polychlorinated Dibenzofurans (PCDF) During a Fire Accident in Capacitors Containing Polychlorinated Biphenyls (PCBs).

72. Rappe, C., et al. Polychlorinated Dioxins (PCDDs), Dibenzofurans (PCDFs), and other Polynuclear Aromatics (PCPNAs) Formed During Fires, Chemical Scripta, Vol. 20, 1982. pp. 56-61.

73. Reference 69, p. 13.

74. Reference 8, p. 23.

75. Haque, R., Schmedding, D.W., and V.H. Freid. Aqueous Solubility, Adsorption and Vapor Behavior of Polychlorinated Biphenyl Aloclor 1254, Environmental Science and Technology, Vol. 8, No. 2, February 1974. pp. 139-142.

76. Polychlorinated Biphenyls (PCBs) Used in Electrical Equipment, Final Rule, 40 CFR Part 761, Federal Register, Vol. 47, No. 165, August 25, 1982. pp. 37342-37360.

77. Bosy, B., et al. Analysis of Public Comments on a Proposed PCB Rule, Prepared by GCA/Technology Division for U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances. Contract 68-01-5960, Technical Directive No. 16, Washington, D.C., August 1982. pp. 68-73.

78. Schecter, A. Contamination of an Office Building in Binghampton, New York by PCBs, Dixons, Furans, and Biphenylenes After an Electrical Panel and Electrical Transformer Incident, Chemosphere, Vol. 12, No. 415, 1983. pp. 669-680.

79. Telephone conversation between Suzanne Ruzinski, EPA Office of Toxic Substances and Robert McInnes, GCA/Technology Division, June 26, 1984.

80. Haile, C.L., and E. Baladi. Methods for Determining the Polychlorinated Biphenyl Emissions from Incineration and Transformer Filling Plants. EPA-600/4-77-078, U.S. Environmental Protection Agency, Research Triangle Park, NC. November 1977. pp. 52-73.

81. Reference 80, p. 54.

82. Telephone conversation between Jane Kim, EPA Office of Toxic Substances and David Misenheimer, Alliance Technologies Corporation (formerly GCA Technology Division), November 18, 1986.